

Relational development site appraisal model for the deployment of Marine Energy
Convertors in Scotland

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ABSTRACT

The use of GIS tools in marine spatial planning has become widespread. Such tools however often prescribe sterilized zones from a developer's perspective (e.g. protected areas) and use surrogate indicators of wave and tidal resource with these being used to suggest areas of likely commercial development.

The work undertaken in this thesis follows a more dynamic approach which has developed software to model the development appraisal process for wave and tidal projects. This means the most economically feasible sites for development can be located, taking into account factors (such as cable costs) ignored where resource parameters alone are used in marine spatial planning.

Moreover the model developed enables contrasting scenarios for differing harvesting technologies, grid connection points, cable types, port facilities to be examined and for specific improvement plans for such infrastructure to be investigated.

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DECLARATION STATEMENT

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- | | | |
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- | | | |
|-------------|--|----------|
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GLOSSARY

= - Equal

<> - Not equal

≥ - Greater than or equal

≤ - Less than or equal

3rd Generation programming language - Computer environment that allows the development of block structured programming.

4th Generation programming language - Computer environment that allows the development of event driving programming and graphical user interfaces.

33kv - 33 kilovolts, a standardised High Voltage rating.

132kv - 132 kilovolts, a standardised High Voltage rating.

AND gate - A logical operation that behaves according a truth table where a true output is only gained when both inputs are true.

ANM - Active Network Management scheme.

ArcGIS - Geographical Information System (GIS) software package.

Batch processing - a series of commands/scripts/programs that are run from start to finish without intervention.

BERR - Business Enterprise and Regulatory Reform.

Binary - A representation for numbers using only two digits 0 and 1.

Bitmap - Raster memory organisation of a file format used to store digital images.

BODC - British Oceanographic Data Centre.

Boolean - binary truth values of 0 or 1.

BWEA - British Wind Energy Association

CD ROM - Compact Disc Read Only Memory.

Combo (combination) box - Windows Graphical User Interface (GUI) facility to allow predefined user input (data) to be selected from a list at run time. Also referred to as drop down menu.

Command button - Windows Graphical User Interface (GUI) facility to allow code (such as to open a new Form Window) to be executed from a specific place, i.e. a button.

dBase - Database software package which was one of the first widely used Database Management System (DBMS) for Microcomputers.

DCF - Discounted Cash Flow.

DECC - Department of Energy and Climate Change.

Defra - Department for Environment, Food and Rural Affairs.

Drop down menu - Windows Graphical User Interface (GUI) facility to allow predefined user input (data) to be selected from a list at run time. Also referred to as Combo box (Combination box).

DTI - Department of Trade and Industry.

DVD - Digital Versatile Disc, an optical disc storage format.

EDF - Electricite de France.

EEZ - Exclusive Economic Zone.

ENSG - Electricity Networks Strategy Group.

EMEC - European Marine Energy Centre.

Excel - A Microsoft product allowing mathematical analysis of data via a variety of tools and spreadsheets.

Event Driven Programming (EPD) language - A computing feature that allows computer code to be controlled by user events, i.e. a window based language to allow the development of windows applications/graphical user interfaces. EPD can also be defined as a 4th Generation Programming Language.

Form - Windows Graphical User Interface screen which will in most cases contain many other Graphical User Interface items.

For loop - A function within a programming language that allows code to be repeated for a given length of time.

GEBCO - General Bathymetric Chart of the Oceans

GIS - Graphical Information System, designed to capture, store, manipulate, analyze, manage, and present all types of geographically referenced data.

Google Earth - Open sourced GIS based system.

Google Maps - Open source mapping system that can be integrated with Google Earth to allow a front end display for GIS data.

GUI - Graphical User Interface.

GW - gigawatt, equal to one billion (10^9) watts or one thousand (10^3) megawatts.

High level programming language - Programming environments where English syntax is used rather than binary or hexadecimal code. Languages of 3rd generation onwards.

Human Computer Interaction (HCI) - A term used for the study of the usability of computers and computer software.

HVDC (High Voltage DC) - a High Voltage category that uses Direct Current technology.

ICIT - International Centre for Island Technology, Heriot-Watt University.

IDRISI - Geographical Information System (GIS) software.

IRR - Internal Rate of Return

km - Kilometre, equal to one thousand (10^3) metres.

kW/m kW/m² - kilowatt per metre and kilowatt per metre squared , common units of measurement for wave and tidal energy resource.

kV - kilovolt, equal to one thousand (10^3) volts.

kW - kilowatt, equal to one thousand (10^3) watts.

Kriging - An interpolation technique for obtaining estimates of unknown value from a set of neighbouring control point values.

Latitude (Lat) - A system of referencing relative north-south locations on the earth's surface. It is measured in degrees (°), minutes (′), and seconds (″) north or south of the equator, incrementing to the poles.

List box - Windows Graphical User Interface (GUI) facility to allow list data to be displayed.

LNR - Local Nature Reserves.

Longitude (Long) - A system of referencing relative east-west locations on the earth's surface. It is measured in degrees (°), minutes (′), and seconds (″) east or west of the Prime Meridian which runs through Greenwich, England.

Macro - A method in Microsoft office terms to allow multiple commands to be executed.

MNR - Marine Nature Reserves.

Matrix - A rectangular arrangement of rows and columns containing data entries or matrix elements.

MapInfo - Geographical Information System (GIS) software.

MEC - Marine Energy Convertor, generic term for both wave and tidal devices.

Megawatt - The megawatt is equal to one million (10^6) watts, or one thousand (10^3) kilowatts.

Megawatt hour (MWh) - unit of energy equal to the work of one megawatt acting for one hour. 1 watt hour equals 3600 joules.

Metres per second (ms⁻¹) - Common unit of measurement for tidal energy resource, in particular tidal velocity. 1 ms⁻¹ = 1.9438 nautical miles (knots)/ 2.2369 miles per hour.

Microsoft (MS) - Software company, producer of many products such as Visual Basic, Excel, Access, Office.

MSP - Marine Spatial Planning.

MSS - Marine Scotland Science.

MS (Microsoft) - Software company, producer of many products such as Visual Basic, Excel, Access, Office.

MW- Megawatt, equal to one million (10^6) watts, one thousand (10^3) kilowatts.

m - Metres.

NA - in model terms a spatial area that is not processed by the model as no marine data exists, such as a location on land.

na - in model terms a valid spatial area which has produced an invalid result from one or more of the calculations undertaken at this location.

NNR - National Nature Reserves.

NPV - Net Present Value.

Nested for loop - A looped section of code nested within another loop. This allows multiple datasets (or various locations within the same dataset) to be read and compared within the same section of code.

Ofgem - Office of Gas and Electricity Markets.

OIC - Orkney Islands Council.

OREF - Orkney Renewable Energy Forum.

Pseudo code - high level description of the operating principle of computer programming and algorithms.

PTO - Power take off.

Radio button - Windows Graphical User Interface (GUI) facility to allow a user to select only one of many logical options.

RAMSAR - Convention on wetland sites.

Random access file format - Feature available in Visual Basic to allow text files to be read as a matrix, therefore any row/column can be read without having to read the entire file.

Raster data - Cell data arranged in a regular grid pattern in which each unit (pixel or cell) in the grid is assigned an identifying value based on its characteristics.

Raster/vector conversion - To convert data from raster format to vector format with position and orientation selected by the user. Also known as a raster-to-vector conversion, or vectorization.

ROCs - Renewables Obligation Certificates.

ROS - Renewable Obligation (Scotland).

R - Programming language and software environment for statistical computing and graphics.

Script - Combination of computer code to undertake a specific task.

SEA - Strategic Environmental Assessment.

SHETL - Scottish Hydro Electric Transmission Ltd.

Spreadsheet - function within Microsoft Excel with tools to capture, analyze, and share two-dimensional matrix datasets.

Sequential file access - A file format in Visual Basic that contains only data and no information as to how this data is stored. Therefore data has to be read from the start to finish regardless of where the data are stored within the file.

Spherical geometry - the geometry of the two-dimensional surface of a sphere.

Spring/Neap tides - Approximately twice a month (around new and full moon) when the sun, moon and Earth form a line tidal forces are increased. This is when the tidal range reaches its maximum and is called the spring tide. When the moon is at first quarter or third quarter, the sun and moon are separated by 90° when viewed from the Earth, and the solar tidal force partially cancels that of the moon. This is when the tidal range reaches its minimum and is called the neap tide.

SSMEI - Scottish Sustainable Marine Environment Initiative.

SAC - Special Areas of Conservation.

SPA - Special Protection Area.

SSSI - Sites of Special Scientific Interest.

Software package - overall software product when viewed as an entire collection.

Text box - Windows Graphical User Interface (GUI) facility to allow short data strings to be displayed.

Truth table - A mathematical table used in logic to compute whether an expression is true for all legitimate input values.

UKDEAL - UK offshore oil and gas information.

UKHO - UK Hydrographic Office.

UNIX - Computing operating system.

UNESCO - United Nations Educational, Scientific and Cultural Organization.

UN - United Nations.

VBA (Visual Basic for Applications) - A form of the Visual Basic programming language that can specifically be integrated with Windows applications such as Microsoft Access, and Excel.

VB (Visual Basic) - A high level computing programming language produced by Microsoft. VB can be used as a block structured and event driven programming environment.

VRML - Virtual Reality Modelling Language.

Watt - Derived unit of measurement of power, defined as one joule per second and measures the rate of energy conversion.

Windows - Operating system produced by Microsoft.

XYZ file format - Text file containing latitude longitude and water depth/land height data.

CHAPTER 1 - INTRODUCTION

With the continued development and success of prototype Marine Energy Convertors (MEC), Scotland can legitimately be described as being at forefront of the marine renewable energy industry through its research, development, and testing facilities. The majority of the leading companies involved in the industry have a presence in Scotland, either as Scottish based companies, or foreign businesses utilising the world leading test facilities and centres of academic excellence available.

It is also apparent that commercial energy extraction by these devices is a feasible prospect. Detailed research and assessments will however, be required to identify specific marine resources and sites that will be best suited for commercial development. There are many restrictions and criteria that will determine the suitability of any particular site for offshore energy development, some of which have been partly addressed by previous work such as the Strategic Environmental Assessment (SEA, Faber Maunsell, 2007) commissioned by the Scottish Executive. This thesis offers a more dynamic approach to allow more flexible analyses of specific site suitability than the generic site assessments provided to date.

1.1 Overall project aim

The main aim of this research was to construct a coherent spatial model that can answer marine renewable development and planning questions such as the best suited locations to install a particular MEC in Scotland. Once potential sites are identified an indication of the cost to develop a site with any particular device is given. The results of this development appraisal approach allow easy identification of potential commercial sites, i.e. a technology neutral developer will be able to use such a model to determine which method would best suit a site. In order to manage the required data analysis, and user requirements, a software application was required to encapsulate all elements and operations.

1.2 Research methodology

The line of study follows a methodology not dissimilar to a marine spatial planning exercise with sensitivity analyses to highlight any particularly sensitive attributes. This

is required to identify feasible locations from a range of varying constraints. This in turn allows an economic model to be formed, providing an estimated cost to install a MEC with due consideration of all of the attributes and constraints. The model design must be dynamic in that it can be used for any location with any technology, i.e. any MEC with the characteristic variables at any site will be processed by the model to produce an end result that represents a cost indication within a spatial context. Therefore, a detailed map of sites (which can be built up to include nested multiple sites or even bodies of water) has to be constructed to show the estimated cost for any particular MEC deployment.

Of particular emphasis to the research is the development of a relational economic model that can be explicitly linked to the technologies, site restrictions and suitability criteria, and their spatial distribution. Many of the restrictions and criteria can be evaluated straightforwardly on a monetary (cardinal) scale enabling the use of cost benefit tools in the spatial modelling. Others need to be evaluated by (ordinal) non-monetary sensitivity expressions e.g. importance for sensitive seabird populations.

The method adopted is a computer modelling approach and applied to marine planning and appraisal specific to the wave and tidal sector of renewable energy. This was achieved by using a modelling methodology implemented using a high level computer programming language working with various datasets to represent the study area. Thus, the datasets in many ways act as layers where each layer contains a specific piece of information for each given geographical site.

Thus, the model methodology (by constructing a dynamic software package, with the ability to add/amend data and run distribution models) uses the data to formulate an answer to specific marine renewable planning and development appraisal questions. This provides a powerful and more relevant tool than a traditional (static) marine spatial planning project undertaken using a GIS package, such as ArcGIS, IDRISI, MapInfo etc.

1.3 Renewable energy policy

Scotland has significant quantities of fossil fuel deposits, nevertheless the Scottish Government has set ambitious (and ever evolving) targets for renewable energy

production, as the various renewable industries gather pace, and the political appetite for the use of sustainable energy grows larger.

The Scottish Government's policy demonstrates its wish to lead the way in marine renewables (RenewableUK, 2011). This recognises the success of Denmark's contribution to the wind industry (global export market worth over 5.7 billion euros in 2008, a 20% share in the global wind turbine market and employing 28,000 workers) when a significant portion of the initial research and development took place in Scotland (RenewableUK, 2011). In 2009 the total employed in the European wind sector totalled 192,000 (European Wind Energy Association EWEA, 2009). Scotland can see a similar opportunity for marine renewables, with the current assumed "world leading" status in marine renewables sustained by continued investment (Scottish Government, 2010).

The appetite for an increase in renewable energy is clearly apparent with rising renewable and emission targets, even over a short period of time. In 2005 the Government set a target aim for 18% of Scotland's electricity production to be generated by renewable sources by 2010, rising to 40% by 2020. In 2007 this was increased to 50% of electricity from renewables by 2020, with an interim target of 31% by 2011 (Scottish Executive, 2005). The following year new targets to reduce overall greenhouse gas emissions by 80% by 2050 were announced. In 2011 this was further increased to 100% of electrical demand by 2020 (Scottish Government, 2011).

The UK government has set a target to cut the UK's carbon dioxide emissions by 60% by 2050. The change of UK government in 2010 (for the first time in 13 years) has also brought a change of thinking on a range of policy issues, and there is now a stated ambition that the new Conservative-Liberal Coalition is to become the "Greenest government ever" (Cameron, 2010).

The new government's first spending review was in November 2010 where DECC was allocated £200 million towards the development of low-carbon technologies over the next 4 financial years, starting from April 2011. £60 million of this fund will be directly allocated to port development to facilitate offshore wind, and it is still unclear how the remaining fund will be invested within renewables.

The positive political attitude towards renewables has resulted in major investment in research and development in Scotland. One of the best examples of this is the European Marine Energy Centre (EMEC) which has dedicated state of the art testing berths linked to a data centre for both wave and tidal devices. A facility such as EMEC is critical for trials and testing, and therefore, development of MECs. At present only a handful of MECs have fulfilled a test programme at EMEC and full scale deployment is still a significant step away for most developers. This has also now been addressed by EMEC who have introduced nursery wave and tidal testing facilities (non grid connected) within the centre, with the first tidal scale device successful deployed late September 2011 (EMEC, 2011).

Scotland already has an impressive renewable portfolio with plans for future growth. According to RenewableUK from the overall ~10.5 GW demand, 1.4 GW is generated from Hydro Electric schemes, and 3.5 GW from onshore wind (at the beginning of 2010) which is the fastest growing renewable industry at present (RenewableUK, 2011). Taking into account the MEC installed capacity, as of March 2012 there is 3.75 MW of installed marine energy capacity which is likely to expand to ~7 MW by mid 2012 (EMEC, 2012).

There are many predictions in the public domain as to potential installed marine capacity, which are generally high. The Forum for Renewable Energy Development in Scotland's (FREDS) Marine Energy Group's (MEG) Marine Road Map published at the end of 2009, outlined a high scenario of 2 GW of installed capacity by 2020 (Forum for Renewable Energy Development in Scotland FREDS, 2009).

In UK terms it has been predicted that marine energy could provide 20% of the UK electricity consumption, from a practically extractable resource of 36 GW. The sector currently employs 800 full time employees in the UK (RenewableUK, 2011). According to RenewableUK there is an indication that 60 MW of cumulative marine energy projects are being planned for deployment by 2014, most of which are within Scottish waters. These figures are the result of an industry study of 13 of the leading technology developers, international utilities and the Crown Estate.

Financial aid to the marine renewables industry also exists in the form of the Renewables Obligation. This scheme places an obligation on UK suppliers of

electricity to source an increasing proportion of their electricity from renewable sources. In Scotland this takes the form of the Scottish Government Renewables Obligation (Scotland) (ROS). According to the Scottish Government the scheme allows Scotland to be the most attractive long-term market for private investment in the marine energy sector anywhere in the world. Similarly, Wave and Tidal Energy Support Scheme (WATES) is clear evidence of the Scottish Government's commitment, and the priority which it attaches to supporting this sector (Forum for Renewable Energy Development in Scotland FREDS, 2009).

A Renewables Obligation Certificate (ROC) is granted for each MWh of renewable output generated. The system was introduced in 2002 by the Department of Trade and Industry (DTI), the Scottish Executive and the Department of Enterprise Trade and Investment respectively, and is administered by the Gas and Electricity Markets Authority (whose day to day functions are performed by Ofgem) (UK Government 2009). Suppliers meet their obligations by presenting sufficient ROCs. Where suppliers do not have sufficient ROCs to meet their obligations, they must pay an equivalent amount into a fund, the proceeds of which are paid back on a pro-rata basis to those suppliers that have presented ROCs (UK Government 2009). Various renewable technologies have different ROC bands with marine being higher at present to represent the stage of the industry. Currently, wave is set at 5 ROCs with tidal 3, although there are various campaigns to increase tidal to be the same as wave. The Renewables Obligation scheme has now been under review since October 2011. DECC initially planned to publish the results of this review in 2012 (Ofgem, 2011) and at the time of printing no update has been released.

Alongside the Renewables Obligation is the Climate Change Levy (CCL), which is another government mechanism for encouraging renewable energy. Introduced on the 1st April 2001, this is a tax on energy use by both business and public sectors. The principal aim of the levy is to encourage non-domestic electricity users to become more energy efficient and so reduce carbon emissions. The levy package as a whole was expected to save millions of tonnes of carbon with all revenue raised being recycled back to business through cuts in employers national insurance contributions, and additional support for energy efficiency and low carbon technologies (HM Revenue & Customs, 2011).

The Government is also offering substantial incentives such as the Saltire Prize to marine renewable developers. This is a £10 million prize to the first developer to produce 100 GWh over a continuous 2 year period, or the developer to convert the most energy by 2017 (Scottish Government, 2011, 2).

A significant amount of interest has been created by the recent Crown Estate leasing rounds, described in detail in *Chapter 2*. The planned delivery for the Pentland Firth and Orkney waters round one sites, represents a total installed capacity of 1.6 GW, which involves 11 sites, 6 wave (600 MW) and 5 tidal sites (1000 MW). A further Scottish leasing round is currently open for the rest of Scotland's territorial waters with applications of up to 30 MW per site. The leasing rounds and Saltire Prize have been identified as encouraging one and another, and therefore promoting development in Scotland as a whole.

Therefore, it can be seen that high level policies are encouraging the marine renewable industry to grow. As a result, one of the benefactors of this funding, EMEC, is a facility that is starting to flourish with a significant number of new devices being installed on both the wave and tidal sites. The latest successes of EMEC are shown in the centre's financial system, where revenue made from developer berth fees is now the main source of funding. EMEC's mission statement is clear and in line with the Scottish Government's aspiration. "To be the internationally acknowledged leading test and certification centre for marine energy converters" (EMEC, 2011, 2).

Once developers have the confidence to go commercial after testing at a facility such as EMEC, the next logical step is to deploy MECs at suitable sites. This combined with the current thrust for marine renewables in terms of national policy means a robust tool is required for site selection in terms of what is technically feasible, quantifying potential constraints and how these will affect the cost of device and array developments. This is where the strengths of this research are to be realised, by providing a dynamic software package (tool) to identify such sites in a technology specific manner.

1.4 Marine Spatial Planning

As the work within this research has been identified as a programme not dissimilar to that of Marine Spatial Planning (MSP), it is valuable at this point to explore MSP and how this project fits (and otherwise) with the principles of this technique. MSP has come into existence to help manage the increasing human demand for marine resources. As not all outputs from the marine resource can be expressed in monetary terms (such as environmental attributes such as habitats) markets find it difficult to perform allocation tasks. Some form of public process is therefore required to decide what mix of resources from the marine environment will be produced over time and space (UNESCO, 2010).

MSP can be described as a tool that brings together multiple users of the marine environment to make informed and coordinated decisions about how to use marine resources sustainably. MSP extensively uses mapping techniques to create a more comprehensive representation of the activities of the marine environment.

There is an increase in the development pressure for sectors that rely on the natural resource of the sea and sectors that use the space and location advantages offered by the marine environment; in combination they create potential conflicts that a marine spatial planning system could help to resolve (Tyldesley, 2004).

Therefore, MSP is defined as an integrated, policy-based approach to the regulation, management and protection of the marine environment. This includes the allocation of space that addresses the multiple, cumulative and potentially conflicting uses of the sea and thereby facilitates sustainable development (Department of Environment, Food, and Rural Affairs Defra, 2006). Defra also explain one of the key characteristics of MSP is the ability to integrate policies across different sectors of activity.

MSP can also be defined as a public process, analysing and allocating spatial and temporal distribution of human activities in the marine environment to achieve ecological, economic and social objectives that usually have been specified through a political process. It is a practical way to create and establish a more rational use of marine space and the interactions between its uses, to balance demands for development

with the need to protect the environment, and achieve social and economic objectives in an open and planned way (UNESCO, 2010).

MSP is described as operating within three dimensions, i.e. addressing activities: on the seabed, in the water column; and on the sea surface. This allows the same space to be used for different purposes (European Commission, 2008).

1.4.1 MSP background and history

Although MSP is experiencing increased application and importance around the world, it is not entirely a new technique as marine zoning (albeit in a sector by sector, case by case basis) took place even before the inception of MSP. The most obvious examples of this include fishing grounds, exclusion zones (such as military, and later with the oil and gas industry) and shipping lanes. As more pressure was put on the environment, and ever new expanding industries that are often in competition, more consideration of the effects on other human activities and the overall marine environment were emerging. This ultimately led to the initial concept of MSP, and one of its primary tools which is zoning, stimulated by international and national interests in developing marine protected areas (MPAs) (European Commission, 2008).

The first application of MSP technique as we know it today was as a management approach for the conservation in the Great Barrier Reef Marine Park (GBRMP), encompassing 2,300 km of coastline. The area of the GBRMP is approximately 344,400 km², making it one of the largest marine protected areas in the world, containing one of the world's richest and most diverse ecosystems. The GBRMP was established by the Great Barrier Reef Marine Park Act of 1975 (UNESCO, 2010, 2).

The perception that the condition of the Great Barrier Reef was degrading, was a fundamental driver in the process of establishing the marine park in the late 1960s and early 1970s. The main threats included oil drilling and limestone mining, pollution from shipping, land-based sources of pollution, and increased fishing and tourism activity (UNESCO, 2010, 2).

Another well known example of MSP is the Florida Keys National Marine Sanctuary in the United States which covers an area of 9,600 km² and stretching 350 km south and

west from the Florida mainland. It was designated as a national marine sanctuary in 1990 under the Florida Keys National Marine Sanctuary Act (UNESCO, 2010, 3).

In 1997 Canada became the first country in the world to adopt comprehensive legislation for integrated ocean management. By passing its Ocean Act, Canada made a commitment to conserve, protect and develop the oceans in a sustainable manner (UNESCO, 2010, 4).

Belgium was among one of the first countries to implement an operational, multiple-use MSP system that covers its territorial sea and exclusive economic zone (EEZ) entitled a Master Plan for the North Sea, which has been implemented incrementally since 2003. The Belgian section of the North Sea covers around 3,600 km² with a 66 km coastline which is intensely used. The main driver for spatial planning in Belgium came from the demand for offshore wind energy and international requirements for the protection and conservation of ecologically and biologically valuable areas (UNESCO, 2010, 5).

In 2002 the Irish Sea Pilot Project researched options for developing, implementing, and managing MSP in all UK offshore waters. The study had two key objectives: to obtain a better understanding and appreciation of available evidence and experiences to date in the field of MSP and its relevance and applicability to UK marine and coastal waters; and to undertake a pilot project to determine the feasibility and practicality of developing and applying a MSP (Department of Environment, Food, and Rural Affairs Defra, 2006).

MSP is required in Scottish and UK Marine Acts as a key tool to achieve more sustainable management of the marine environment. In 2008, informed by the 2002 Irish Sea Pilot, the UK introduced a Marine and Coastal Access Bill and Marine Scotland Bill into Parliament. This followed consultation documents in March 2006 and 2007 and a draft Marine Bill in April 2008. At a strategic level the UK recognised the potential benefit of MSP in addressing the need for a more coherent and integrated approach to the threats from on-going and increasing use of the marine environment (Scottish Government, 2010).

Through the Scottish Sustainable Marine Environment Initiative (SSMEI), the Scottish Government is also developing and testing new approaches to marine management.

The initiative has entered its third and final phase, with four pilots now established in Berwickshire, Clyde, Shetland and the Sound of Mull (Scottish Government, 2011, 3).

1.5 Previous similar work undertaken within Marine Spatial Planning, marine renewable planning and other related research

At the time this research was initiated, it became apparent the Scottish Executive were going to produce a Strategic Environmental Assessment (SEA). The overall objective and original study area initially looked to be similar to this research, however it was clear that the methods and aims of the research were different.

There has been a significant amount of other work undertaken, which has helped this research rather than requiring it to take a change of direction. The main research within the related fields are as follows:

1.5.1 Strategic Environmental Assessment (SEA), by Scottish Executive

Strategic Environmental Assessment (SEA) is the process of appraisal through which environmental protection and sustainable development may be considered, and factored into national and local decisions regarding Government (and other) plans and programmes, such as oil and gas licensing rounds and other offshore energy developments. The process aims to help inform Ministerial decisions through consideration of the environmental implications of the proposed action. The Department of Energy and Climate Change (DECC), as the principal regulator of the offshore oil and gas industry, has taken a proactive stance on the use of SEA as a means of striking a balance between promoting economic development of the UK's offshore energy resources and effective environmental protection (DECC, 2011).

The Scottish Executive SEA was undertaken by consultants Faber Maunsell, in association with Metoc plc, an environmental engineering consultancy. The aim of the Scottish Executive SEA was to enable a better understanding of the environmental impacts from wave and tidal energy development around the west coast of Scotland from the Mull of Galloway northwards to Orkney and Shetland, including the Pentland Firth. The executive also stated that the SEA will help shape planning guidance, and

steer project developers to the best sites for device deployment. Essentially this is achieved with the study of a number of spatial constraints.

The study area was described as the regions with the most significant interest for the development of wave and tidal devices, after consultation with developers and their steering group. Therefore, the study area focused on the western seaboard of Scotland, the Pentland Firth and the Northern Isles. It was concluded there was no evidence that developer would be interested in the east coast of Scotland. The Solway Firth is also not included.

The research in this thesis covers the areas of greatest interest, however it was also considered appropriate to look at areas not covered in the SEA. When considering electrical grid and port/maintenance facilities, the east coast and Solway Firth is in a stronger position for both, even although the resource is probably further from land and not as substantial.

In the SEA St Kilda was initially identified as a potential site, probably due to the fact it has a significant wave resource, however, the area has little in the way of infrastructure. St Kilda does not fare favourably in the various logical tests within the model constructed by this research, where a different approach has been used to that adopted by the SEA.

Within the SEA there is a fairly comprehensive list of both wave and tidal devices with 22 wave and 17 tidal devices having been identified, which accounts for around 36% of the devices identified in the technological review that was undertaken as part of this research. A more detailed analysis of the various device categories was undertaken in the technological review, and as more devices were identified, a fuller categorisation method could be formulated.

1.5.2 Department of Trade and Industry (DTI) UK marine renewable energy atlas

In 2004, a UK marine renewable energy resource mapping project was completed by the Department of Trade and Industry (DTI), which was replaced by the Department for Business Enterprise and Regulatory Reform (BERR) as of June 2007, and later in October 2008 by the Department of Energy and Climate Change (DECC). This project

was a consortium led by ABP Marine Environmental Research (ABPmer), which included the providers of major marine data holdings, and provided the renewables sector with a spatial distribution for the wind, wave and tidal resources, to the boundary limits of the UK continental shelf. In 2008, an updated version of the DTI Atlas (as it is commonly known) was available with improved underlying resource datasets (BERR 2008, 2).

One aim for the atlas was to assist decisions on future rounds of licensing for large-scale deployment of marine renewable technologies. This work was undertaken as part of the DTI led Strategic Environmental Assessment (SEA) combined programme covering oil & gas and marine renewable agendas.

Initially, a SEA was undertaken for the areas proposed for offshore wind farm developments (DECC, 2003). While the consultation focused on offshore wind energy, the Government indicated that it wished to ensure that the proposed planning framework was also appropriate for other offshore technologies such as tidal stream and wave energy devices. This was the view before the dedicated SEA for renewables was undertaken, and before the introduction of wind energy to the general oil and gas SEA that the DTI also undertook.

The work completed by the DTI for the atlas has been invaluable for this research. The data behind the Atlas is available and was reformatted to enable its use by the model developed in this research.

1.5.3 The Department for Environment and Rural Affairs (Defra) Irish Sea pilot

In 2002 Defra produced a document designed to illustrate what a marine spatial plan for the Irish Sea could look like and what it might contain. It had been produced by a process that also simulates strategic plan making and includes stakeholder consultation. The plan is supported by a number of scenarios that have been developed to indicate how the information might be used to make spatial allocations for certain future uses (Department of Environment, Food, and Rural Affairs Defra, 2004).

The pilot collated geophysical, hydrographical, nature conservation, ecological and human use data and used GIS analysis. While intertidal and near coast biological

information was found to be satisfactory, data were sparse for most offshore localities to a degree which would constrain good decision making. Undertaking this work led to a better understating of MSP, and various recommendations for future MSP projects in the UK were made. (Department of Environment, Food, and Rural Affairs Defra, 2004).

1.5.4 Shetland Marine Spatial planning project

Shetland's MSP brings together authoritative spatial data on the marine and coastal environment and its various uses. It establishes an overarching policy framework to guide the placement of activity, from marine renewable energy to aquaculture.

The plan has benefited from extensive consultation with a wide range of stakeholders since the project began in 2006, including a public consultation and trial implementation. (IronsideFarrar/Scottish Sustainable Marine Environment Initiative (SSMEI), 2010)

As a related piece of work in Shetland, working in tandem with the MSP project, a one year research programme was undertaken to look specifically at the marine renewable potential for the Shetland Isles (Wemyss, 2010). This work concluded (in consultation with the BERR renewable atlas, and various initial findings from this research) that a resource study should be commissioned for the Shetland wave and tidal resources, which was completed in 2011 (NaturalPower, 2011).

1.5.5 Other related work

The MSP detailed above is mainly concerned with zoning and policy driven mapping. In terms of finding suitable sites where specific MECs could be deployed, there are several studies available. The most notable early publication is the EC Joule report conducted in 1996, which examines the resource, technology and economics relating to the possible exploitation of offshore tidal and marine currents as a future source of energy within the European Community. The technological review within the report details only six designs that had been used to that point. The economic discussion was based around the construction costs of the devices (European Commission, 1996).

In 2003 an earlier piece of work to this research (Wemyss, 2004) was undertaken to identify potential tidal development regions within the Pentland Firth using 3 forms of

tidal technology. This followed work undertaken by ICIT in the form of feasibility studies for the placement of tidal devices in the Pentland Firth (Bullen and Dacre 2002), which was undertaken in conjunction with Robert Gordon University, and potential tidal sites for Orkney and Shetland (ICIT and European Union, 1995).

Strathclyde University have undertaken various studies mainly addressing the Marine Current Energy Baseload Supply Strategy for Scotland (Akwensivie *et al.*, 2004). MSc Students at Strathclyde University's Energy Systems Research Unit also undertook a study in 2006 to investigate the characteristics of the tidal resources in Scotland and demonstrate how to match those resources with the appropriate marine current technology (Glynn *et al.*, 2006).

In New Zealand a study was produced in 2008 by The Electricity Commission (EC), the Energy Efficiency and Conservation Authority (EECA) and Greater Wellington Regional Council (GWRC) to review the current state of domestic and international marine energy technologies and their development and deployment. New wave and tidal energy resource assessments were undertaken by integrating the performance characteristics of modelled wave and tidal devices (Power Projects, 2008). In 2011 the United States undertook a similar exercise with the Mapping and Assessment of the US Ocean Wave Energy Resource identifying the naturally available and technically recoverable U.S. wave energy resource, using a hindcast resource database and selection of wave devices (Electrical Power Research Institute, 2011).

In many ways these studies capture some of the aims of this study in that they look at the technologies available (albeit with just one form or another in most cases) and compare these to physical restrictions, mainly resource. There is little consideration given to planning in spatial terms with other physical and non physical constraints. These studies were also desk top studies using static parameters with no aim to model dynamically the effects of the spatial arrangement (with different devices for example) or to model the effects of changing spatial constraints such as the electrical grid.

More generally there is active research in various other related (albeit less relevant) areas. A multidisciplinary research programme titled: Sustainable Power Generation and Supply (SuperGen Marine) which is managed and led by the Engineering and Physical Sciences Research Council (EPSRC) has undertaken 2 phases of work relating

to marine renewables (EPSRC/Edinburgh University, 2007). For example, work package 6 from phase 1 (“Network interaction of marine energy”) examined the electrical grid around Scotland and how marine renewable energy might be connected. This is in response to the view that the electrical network requires significant reinforcement to allow the vast renewables potential to be harnessed, transmitted and exported (Mather, 2010).

There have been many specific static studies undertaken for MEC deployments, MSP assessments of various environmental constraints, and wave and tidal resource assessments. However, there is no conclusive evidence that these techniques have been used with one another for the specific task of modelling the spatial distribution of devices (both wave and tidal) to produce economic indicators appropriate to development appraisal.

1.6 Weaknesses with the Marine Spatial Planning and previous approaches

Although MSP is a powerful technique and useful planning tool that will undoubtedly aid the successful management of the marine environment, there are some weaknesses in terms of spatial and data modelling which were addressed in this research. This is not a criticism of the MSP technique, as it is not designed to be used in this way.

One of the main MSP tools, zoning, is problematic from a development point of view, as in practice the technique produces “no go” zones that sterilize particular areas. The technique identifies space left over from other marine uses where new or additional activity can take place. The use of zoning has caused concerns within MSP projects. The Shetland MSP project for example stopped short of publishing any zoning work as it was felt to be too academic and restrictive, as well as added risk of labelling open areas that maybe inappropriate for development. (Marine Scotland 2010 / Scottish Sustainable Marine Environment Initiative (SSMEI) 2010).

Mapping produced by MSP is also of a static nature, i.e. outputs are layered maps. The data behind these maps, in many cases, cannot be used to make fully informed decisions, and therefore there is little or no interaction. This is for several reasons: some datasets (maps) are constructed as spatial areas (take a protected area for example) which is a spatial section determined by boundary coordinates and therefore does not

contain any valuable underlying datasets that can be used in modelling. As MSP is essentially a mapping exercise the format and resolution of the underlying datasets is not a concern. Therefore, most datasets differ in these terms, which is an advantage of the system in many ways, as layers can be built up without being restricted to a system format or resolution. However, it makes it difficult to use the datasets with each other for future data manipulation and modelling. In order to use data from MSP projects to a conduct dynamic modelling, further software approaches have to be taken.

As one example it is worth considering a specific question regarding the electrical grid for MEC developments; what affect would a MEC development have on the grid? This can also be reversed by asking how would an upgrade to the grid in any particular area change the spatial distribution of likely development, and the overall cost of this development? These are the sort of questions that MSP presently cannot answer owing to its static nature and application of datasets, data structures and the relationships between them.

Therefore, to achieve automated data modelling where data values (for spatial sites) can be manipulated and tested to obtain dynamic spatial results for specific MEC developments, a new approach was developed.

1.7 Dynamic Marine Spatial Planning tool

This research concentrated on defining the optimal areas for MECs in Scottish waters with a predictive model, rather than taking the traditional option of existing MSP zoned datasets, that identify “free space” within larger areas with potential constraints. In practice, the MSP process usually results in a plan for a marine region, which more often than not, is centred around zoning plans, which grant or deny individual permits for the use of marine space. This may even be a single layer such as a protected area or a shipping lane. Instead of dismissing a site as it has an identified restriction(s), in which a device may not actually have an effect, it is valuable and more efficient to look at all sites initially to define where the most optimum locations are, highlighting the sites where there is the most pressure to develop. The device itself will have physical limitations of course, such as resource, distance to land and water depth.

Generally MSP and policy are interlinked, that is, there is a theme where MSP techniques are used to define policy, and policy using MSP as a method for reinforcement. This research did not attempt to marry, in the modelling undertaken, any form of current or existing policy. A considerable amount of literature surrounding MSP, is how MSP will be (and has been) used within legislative frameworks. (European Commission 2008 and 2010). This normally tackles the questions of how best to achieve a legislative structure using MSP, and how MSP and policy will complement each other. Therefore, MSP can be seen as a tool for management and policy, whereas this research provides a tool for highlighting the most optimal (and feasible) sites specifically for MEC deployments regardless of restrictions in place. This is a task not possible with current MSP techniques.

There are other subtle differences with this project and one taking a more traditional MSP approach. This research is specifically working with existing data and is not working or communicating directly with stakeholders which is a key aspect of a fully developed MSP programme. The modelling within this research also takes into consideration the terrestrial infrastructure that is important for modelling the overall system, such as electrical grid, cabling and port locations.

There is however an inter relationship with MSP, as this research can be used by MSP (that is, layers of data showing where the most optimum, and therefore economical, developments could take place) as an MSP input. This research can also use MSP techniques and outputs (such as datasets used within the process) as inputs to the data modelling processes used. The overall work can be considered to be a part of a MSP process providing information to feed in, or as an extension by taking the information available from MSP and using it in a dynamic modelling fashion. There is also synergy to the outputs of this research and MSP where all outputs will utilise easily understandable spatial mapping, utilising only sound information and scientific knowledge for input parameters, with each step of the modelling process being undertaken in a transparent manner.

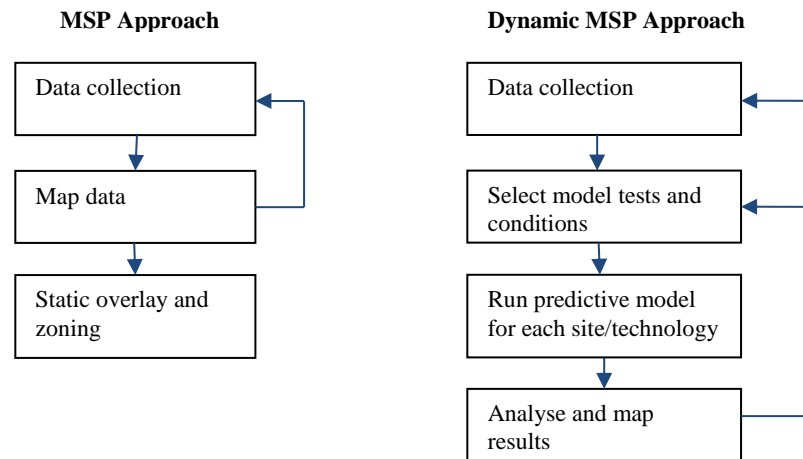


Figure 1.1 showing a view of the simplified approaches taken by a traditional MSP method and Dynamic Marine Spatial Planning tool developed in this research. The MSP approach gathers data which is mapped and used for zoning, while the method in this research tests the available data at each site for each form of technology (variables that can all be changed) to produce dynamic results.

1.8 Research rationale and overarching challenge

In MSP at the present time, data on the wave and tidal resource provides a poor basis for prioritising areas likely to be favoured for commercial development. To do this a full development appraisal is required which must take into account a range of other factors. MSP tends to use spatial factors (such as Special Protected Areas, shipping lanes, fishing grounds etc) as constraints to development within a zoning approach. This can lead to sterilisation. In contrast investors and developers having identified favoured areas for commercial development would tend to view such spatial features as risk and challenges to be overcome in the planning approval and consenting process.

For developers and investors a favoured approach would be one that takes all spatial features necessary for a full commercial development appraisal into account for any given technology and location.

This development appraisal approach, however, could provide a level of detail on areas favoured for commercial development for MSP, replacing the reliance on resource only data. For this, however, the appraisal would have to be undertaken for all possible technologies and locations.

Thus the challenge is really one of incorporating all features necessary for a commercial development appraisal both for a given technology and location, and for all suitable technologies and locations. This provides outputs of value not only for developers and investors, but also for MSP.

1.9 Research objectives and aims

The principal objective of this research is thus one that can satisfy this challenge. In order to do this it is necessary to construct a spatial model which can: incorporate all the elements necessary for a commercial development appraisal for not only a given technology and location, but also for all unsuitable technologies and locations.

In working towards such an objective there are many desirable features that might be incorporated. Some of these are features of any software development (e.g. ease of use) and others are specific to achieving this objective. However some key aims were adopted.

While it would be impracticable to incorporate every single feature in the model from the start, the software developed should be written in such a way as to facilitate the incorporation of additional features, such as new data on technologies, spatial constraints, and data at finer spatial resolutions. The working model should as a priority demonstrate the complete development appraisal process.

1.10 Likely end users and their requirements

An important aim of the project was to produce a software application that although not incorporating all possible features, nonetheless encapsulates the complete operation of the model. This software package acts as a tool for the end user within a Windows interface environment, allowing easy interaction with the various model functionality the application makes available. That is, the model can be used by a range of users and will not need significant background knowledge of the methodology, logic, or any of the technical aspects of the model's code.

It is anticipated that the model will be of significant interest to developers of MECs or developers of MEC deployments such as energy companies using a MEC of their choice, or who are technology neutral. This has been the case already with an energy company already showing interest in the development of this research. This company was progressing plans to install a farm of a proven prototype MEC in Scotland, however they were unsure of the best location. After a technical feasibility study the company selected the specific device that fulfilled their requirements, however, they did not know how (or have the time or resource) to process the site data to determine where the device could be located within their preferred overall area.

The company also had access to a substantial amount of relevant data (for a large specific area) and were unsure of the best method in which to analyse these data in order to make a scientific judgement. What would be the best specific site for their proposed development, considering their favoured device?

In addition to developers it is anticipated that the findings of this research will also be of interest to the Crown Estate and Marine Scotland, as the results will ultimately determine the areas most likely to be developed. Therefore, this will indicate the sites that will be in demand from developers. The findings will also be of interest to marine planning and other researchers in the general subject area.

1.11 Structure of thesis

Chapter 2 details the study area with an introductory look at the parameters that that will need to be extracted from the study area and technologies to produce a model. Chapter 3 undertakes a dataset review and sets out a design for the ideal model. A working design is also set out with the datasets required to undertake this development. Chapter 4 describes the operation of the built model and how it is used. Chapter 5 documents a full set of test scenarios undertaken to ensure the model was built to design. Chapter 6 describes an illustrated example of how the model can be used to show distribution changes. Chapter 7 details how the model could be improved and Chapter 8 concludes the thesis. Appendixes A to H document the low level designs and datasets, and any other detailed information referenced from the main body of text.

CHAPTER 2 – STUDY AREA BACKGROUND AND BOUNDARIES

In this chapter the study area and project boundaries are defined. The characteristics of the main study area are identified to formulate a list of parameters required to build the model. This chapter also introduces the technologies that the model includes.

2.1 The study area

The main study area of the project is Scotland and adjacent seas. The full coordinates of the area are detailed later within *Chapter 3*. The actual area of data covers a wider area than just Scotland and her seas, as the model works from a matrix of data rather than following various contours that are associated with geographical boundaries.

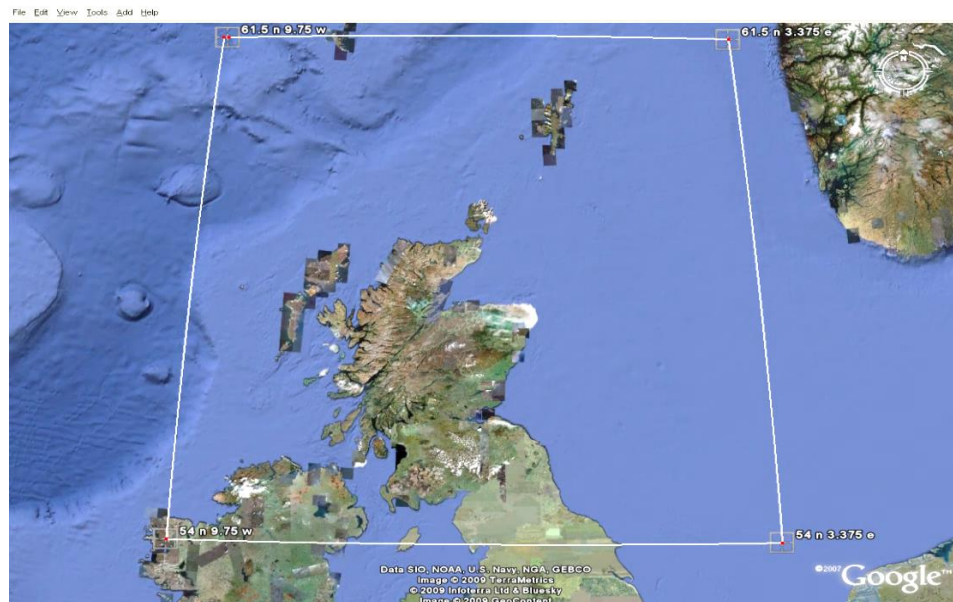


Figure 2.1 maximum geographical boundary of the project.

From north to south the maximum area covered in *Figure 2.1* is approximately 520 miles. From west to east the maximum distance at the south west to south east point is around 535 miles and 430 miles at the north west to east point. Therefore, the area covered is roughly 250,000 square miles. The study area includes areas of inshore, sea and ocean sites. The majority of the northern North Sea is included, as is the northern sector of Irish Sea sector which is relevant to Scotland.

There are areas of data sparseness around the boundaries of the study area and the waters off Donegal (Republic of Ireland) which are fully described in *Chapter 3*. However (and most importantly) the area covered, with present data, encapsulates the significant wave and tidal resource within the Scottish territorial seas and continental shelf.

In the resource mapping produced for the DTI Atlas, the boundaries were variable, with the wave boundaries extending further west than the tidal. At this point it was apparent the wave data beyond the continental shelf also becomes much less detailed. Initially this was a concern which promoted the view that if the DTI data were to be used further, then the boundary of the project may need to follow a consistent size and stay within area of the smaller tidal datasets. However, the final decision was left until a full review of the datasets available was undertaken, and is fully covered later in *Chapter 3*.

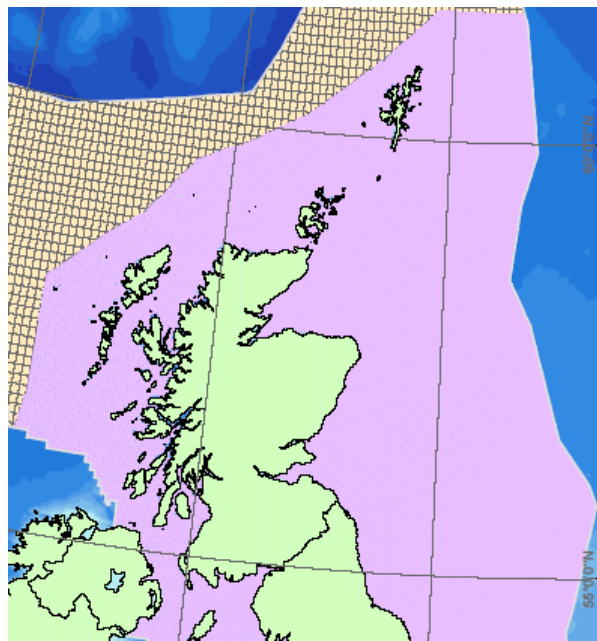


Figure 2.2 showing the DTI data coverage around Scotland. The extent of the tidal data is shown in purple. The wave resource resolution grid can be seen further to the west.

It was apparent that it would be an advantage to design the model in such a way that these boundaries do not need to be fixed, and if data were available (that included a wider area) then these can be accommodated. The same is true for higher resolution data, for example, if more detailed data for a small area (such as the Pentland Firth)

became available, the model could process these by nesting them without needing to be completely redesigned.

2.1.1 Other physical characteristics and resource

The bathymetry of the area is varied with shallow inshore to relatively deep sea areas. The greatest recorded depth within the DTI bathymetry dataset was 248 m, which is an area in the North Sea 125 km east of the Orkney Isles.

The coastline is the boundary the model uses for various distance calculations, i.e. the distance from any site at sea to the shore. The actual physical attributes of the land is not considered other than potentially looking at onshore cable routing. The furthest distance to land within the study area (another position in the North Sea) measures 301 km to eastern coast of Scotland.

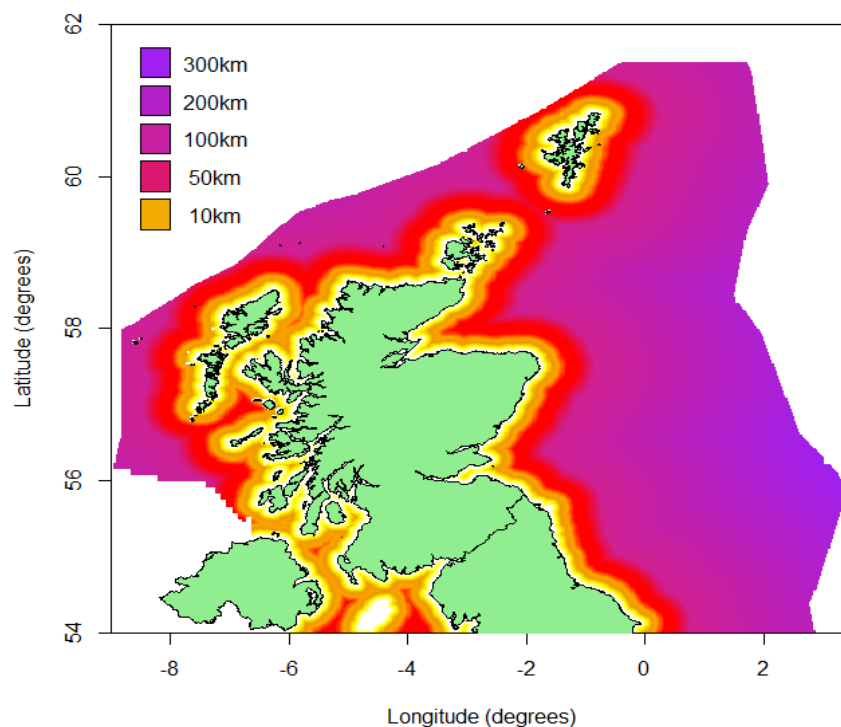


Figure 2.3 showing the range for offshore distances within the study area. This image has been captured using the DTI data, (BERR, 2008).

Within the study area there is also significant natural renewable resources in the form of wind as well as wave and tidal. The wind resource is not considered from a development point of view within this research, however the data is considered useful

for other calculations, for example factoring weather and installation costs at a particular site. The tidal resource (mean spring peak flow) reaches a maximum of 19.129 kW/m² in the Pentland Firth with other significant hotspots around the study area. The wave resource (annual mean wave power) peaks over 50 kW/m in the deep water sites on the west coast.

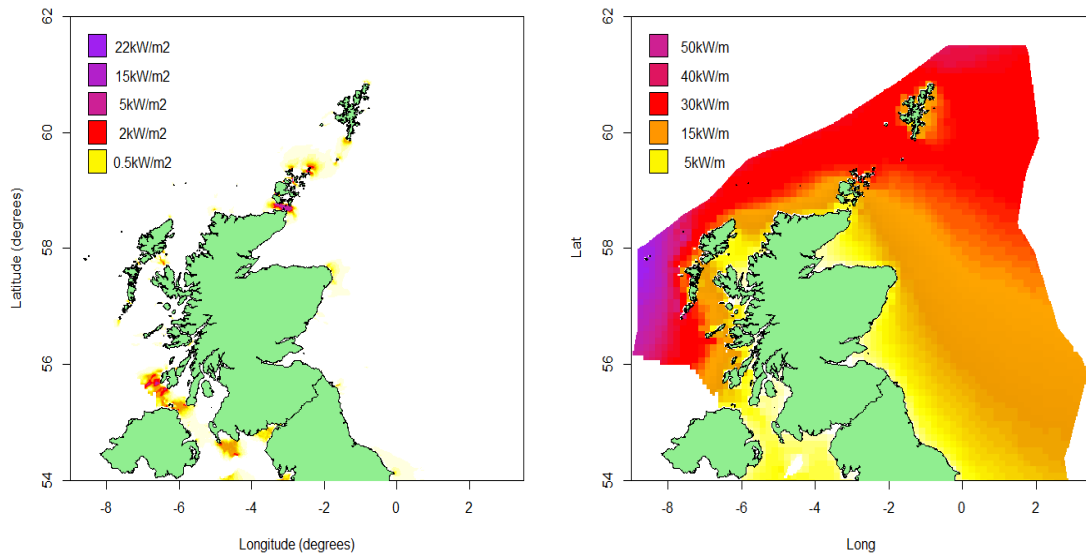


Figure 2.4 showing the annual mean tidal power (kW/m²) for the study area on the left, and the annual mean wave power on the right (kW/m). These images have been captured using the DTI data (BERR, 2008).

2.1.2 Electrical grid

The Scottish transmission and distribution system was designed and developed with large generating power stations transmitting to demand areas, meaning transmission is from a strong central point to weaker peripheries, by 400-275-132 kilovolt (kV) step downs, then delivering power through lower voltage distribution networks. This generally means that the best resources (usually in the most remote areas, and furthest away from the centres of demand) have only a weak distribution network. In Scotland the general rule is that the grid is weak in many rural areas and future upgrades (such as the Beaully to Denny upgrade) are urgently required to help the situation (Electricity Networks Strategy Group, 2009).

An established electrical grid is a must for any renewable project and should be considered as part of any renewable energy research. A major concern for the

renewable energy sector is the capacity of the electrical grid to integrate additional generation, which is also a major national financial concern when considering the cost of upgrades. It is widely acknowledged that substantial upgrades will be required to Scotland's electricity transmission system depending on the level of renewable development to be accommodated (Electricity Networks Strategy Group, 2009).

At the start of 2000, the Scottish Executive, transmission owners and the DTI started to address these grid connection issues, by undertaking various planning exercises to help develop the capability to connect additional renewable generation. Ofgem (the electricity market regulator) proposed a mechanism to fund a number of key Scottish transmission upgrades (Forum for Renewable Energy Development in Scotland FREDS, 2005).

The recommendation made was to upgrade the Beauly-Denny and Sloy links to reduce bottlenecks between north south transmissions, as well as upgrading the south-west Scotland network, and the Scotland-England interconnector. These key upgrades, along with further local reinforcements, could allow the connection of up to 6.3 gigawatt (GW) of the current generation applications, depending on the locations of consented generation schemes (Forum for Renewable Energy Development in Scotland FREDS, 2005).

By 2006 the *Path to Power* report by the British Wind Energy Association (BWEA), concluded the grid connection presented a major hurdle for the development in both northern Scotland and Western Isles.

The 400 kV Beauly-Denny link was approved in 2010 although there is one report suggesting the completion date is slipping, possibly 2015/16 rather than 2013/14, (reNews, 2011). Although the upgraded line must be in place within 10 years to comply with planning conditions, the consent states that construction of the line must begin within 4 years, and that electricity transmission should begin within 6 years of the start of construction. Within the same article (reNews, 2011) the cost has also reported to have escalated to £557 million, from the 2004 estimate of £250 million.

The current lack of availability of grid capacity provides a fundamental barrier to the development of the marine industry, and future reinforcements will require substantial

investment. RenewableUK (Formally the BWEA) see the connection to the Shetland, Orkney, and Western Isles as a priority for the industry (RenewableUK, 2011).

Scottish Hydro Electric Transmission (SHETL) has started to examine a series of new grid connection options for Orkney, such as an additional 132 kV/180 MW link. The Orkney Islands Council (OIC) and Orkney Renewable Energy Forum (OREF) suggest that if things go to plan beyond 2016, a gigawatt scale connections will be required which will most likely be a HVDC connection (Orkney Islands Council and Orkney Renewable Energy Forum 2010). SHETL has investigated a HVDC solution of up to 600 MW to the West Mainland of Orkney and a 300 to 400 MW HVDC to South Ronaldsay. This is mainly being triggered by the Crown Estate leasing rounds which were initiated with the Pentland Firth and Orkney waters. In May 2009 the Crown Estate announced that 42 applications had been received from 20 bidders for the area. The commercial scale out from this leasing round will not take place until 2015/16 with 400 MW of which the majority is around Orkney.

In Orkney the Active Network Management scheme (ANM) gives the potential for generation to be switched off during extreme generation peaks or troughs in demand. This scheme (sometimes also known as “Connect and Manage”) has allowed 15 GW of generation projects around the UK to be offered grid connection dates. The system allows more generation devices to be connected to the grid and improve the efficiency of its use. The ANM initially estimated that perhaps 50 MW of additional capacity could be made available in Orkney which has a baseload of ~20 MW. A report by the OIC and OREF in June 2010, states that the current ANM has been capped at 15 MW and suggests that an urgent review is required to determine how much of the remaining 35 MW could be used and when (OREF, 2010) (Orkney Island Council, 2009).

In the Western Isles, a ANM also exists to enable small generation (< 10 MW) with 75 MW of capacity being available from the latest stage of upgrades, mainly from Fort Augustus to the Western Isles. There is also a proposal for 450 MW HVDC interconnector in late 2014/2015 (RenewableUK, 2011).

Shetland, which is rich in tidal and wave resource, has no connection to the grid. The cost of a link at present excludes marine renewable development and access to this resource is currently reliant on the potential commitment of the 103 turbine Viking

Energy onshore wind project (and resulting HVDC/600 MW interconnecting cable to Moray) which was approved for development April 2012 (Viking Energy, 2012).

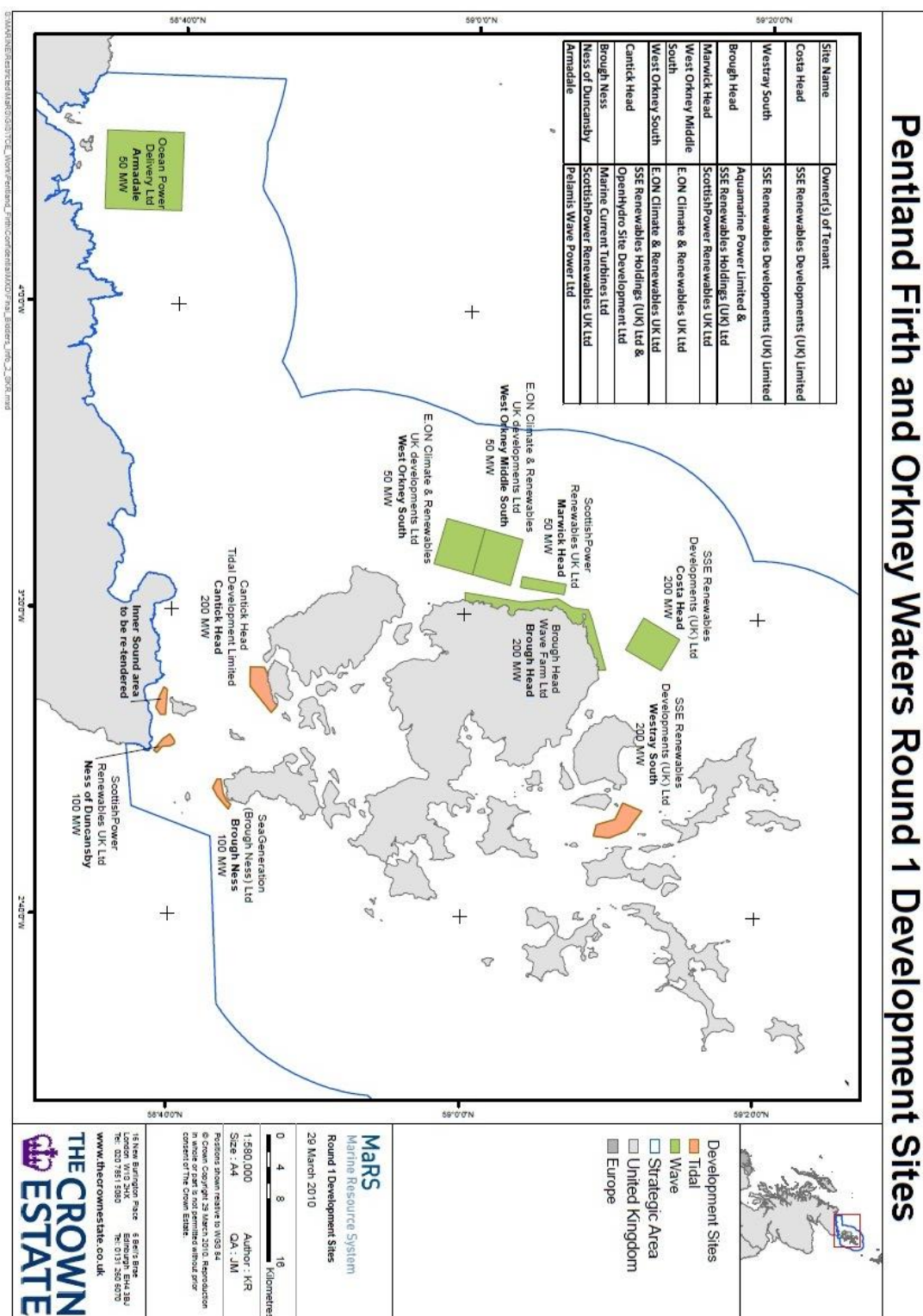


Figure 2.5 Pentland Firth and Orkney waters round 1 development sites. Source Crown Estate.

In addition, there are various plans throughout Scotland to reinforce the electrical network. A brief list of these include: Knocknagael (a new substation to allow 125 MW of export in the north west), a new 275 kV south west Scotland transmission line, and upgrades to the following lines: Beaulay-Blackhillock, Beaulay-Dounreay, Beaulay-Mossford, Kintyre-Hunterston, East Coast transmission route (to 400 kV) and Scotland-England interconnectors to increase the export capacity to 3.2 GW (Scottish Power 2011, Scottish & Southern Electricity, 2011).

Another disadvantage for all renewables is grid connection charges. A variation in connection charges exists, due to losses in power that are incurred when electricity is transmitted on the grid over long distances. The system to regulate this is continually debated, and may change with Ofgem's project TransmiT (Ofgem, 2011, Ofgem, 2011, 2, and Ofgem, 2012).

At present, a location dependent measure reflects the higher loss levels with the increasing distance to demand, that is, high charges are imposed on those projects furthest from the market. The National Grid charging zones have significant implications for the location of renewable generation, as the preferred connection zones are in the south closest to demand, which is unfortunately, furthest away from a significant proportion of the marine energy resource. Therefore the charging system, by default, imposes the highest charges on the areas with the highest renewable resource. In areas with lowest resource/closest to demand, there are often no or negative connection charges.

It is likely that the continual growth of onshore wind power (which also experiences the best resources in remote areas) may help overcome transmission problems, and efforts could also be made to look at other methods to avoid connection problems and charges, such as producing hydrogen by electrolysis, i.e. allowing a product to be exported by batch from a marine energy farm instead of exporting electricity directly to the grid.

In some remote areas it may be more logical to concentrate on supplying local demands, rather than looking at expensive transmission to the central belt. It is also interesting to speculate as to how much upgrading the grid actually requires. An integrated overall upgrade of the system in the future (with the above mentioned AMS methods) could see an efficient and cost effective result considering that traditional power plants do not

need to produce as much power if renewable energy producing to remote sites is successful. However, there is no question that the remote outposts need upgrading to allow generation to be exported, rather than being at the end of the import line.

The grid infrastructure is vitally important to the development of marine renewables within the study area, and is therefore included within the model. The method used to model the grid was a comprehensive list of coastal power stations and connection points. There are also many inland power stations on the grid that are not particularly relevant for the offshore modelling (such as offshore cabling to a development site), however these will be important for the construction of onshore grid modelling.

The number of coastal Scottish power stations (and connections points such as EMEC and oil terminals) is 31. Since the boundary of the project extends to include northern England and the northern area of Ireland, the power stations and connection points from these areas are also included to stay consistent with the other datasets the model used, such as resource. Therefore, this figure is increased to 91 connection points from within and around the study area.

Many of these connection points have limited capacity, however these will still play an important role within the model, as the methodology allows real values (such as capacity) to be altered to witness potential distribution changes. Conversely, by following this methodology the model has the capability to determine what part of the grid needs upgraded for certain developments to be undertaken.

2.1.3 Ports

Scotland has a wide range of ports, and unlike the grid infrastructure, large safe ports are located strategically close to the actual resource. The Northern Isles is probably the best example of this where good tidal and wave resource exist in combination with ports such as Scapa Flow and Lerwick, which are more than capable of accommodating the type of vessels/rigs required for marine energy deployment (Marine Publications Limited, 2006 to 2011).

Ports around Scotland will play an important role in the development of marine renewables and will likely have a bearing on the economics of a site development.

Therefore, datasets were required for ports and harbours in the study area, and along with power landing points, make a significant contribution to the methods used by the research model. The methodology behind the data capture, structure and storage was similar to that of the power stations and connection points.

In conclusion 165 Scottish ports and harbours have been identified. Many smaller harbours are also included, as although too small at present in terms of the size of vessel they can accommodate, they may in the future be upgraded which highlights another important aspect of the model. If a harbour is developed, the model can analyse whether this will affect the cost of a MEC deployment, which if turned the other way around, the model can show which ports should be developed.

2.2 Marine Energy Devices (MECs)

There are various forms of technology emerging in the marine energy sector as various parties try to produce a device that will not only convert marine energy efficiently within a construction and operational budget, but also withstand the harsh operating environment. There has been a substantial amount of work done in the two distinct sectors of wave and tidal technology, with major progress in both sectors in recent years (RenewableUK, 2011).

The wave sector has a longer development history than tidal. However, this does not relate directly to the advance of the two forms of technology in comparison with each other. When many of the wave methods that are included within the research were in development, tidal barrage was the only recognised form of tidal technology, a method which in many senses is considered to be a different sector to tidal current technology. Tidal current technology has advanced quickly and arguably has caught up with wave development, if not surpassed it. From the initial study undertaken to formulate the technological review for this research, a wider range of wave than tidal technologies were found.

One explanation for this is the wave sector has been around longer, allowing a wider range of methods to be developed within this greater length of time. Another (more technical) reason is that the wave resource is much larger with many variations of deep and shallow water waves which are very dependant on location. This has resulted in

various development methods, which are designed to extract, at most, only a very small percentage of the energy in a very specific way.

Therefore, of the two distinct branches of the marine energy the wave sector has developed a diverse range of devices and classifications, simply because there are more ways to extract wave energy. There are schools of thought that believe this broad diversification is a problem for the wave industry (Whittaker and Folley, 2005). There is also a range of fringe products that have reached (or are very close to) commercial status. These niche products have focused on other “work” that marine energy can provide where other conventional methods are expensive. A short overview of this technology is described within this section.

Tidal extraction methods on the other hand have had a shorter time to evolve, and have the advantage of extracting a resource which is more consistent than localised wave regimes. This has resulted in a common design theme that mainly resembles underwater wind turbines, albeit with specialised alterations. In stating the above there are of course a couple of exceptions to this rule with a handful of devices that use other means.

Although MEC technology generally looks at a marine resource to produce electricity, it is worth pointing out that some of the devices have actually been designed to perform other purposes. The majority of devices included (in addition) will be able provide potable water through reverse osmosis, or produce electricity as a primary resource or for the purpose of producing hydrogen. Some devices are also designed in such a way to act as a coastal defence as a secondary effect of extracting energy for one of the above main purposes. All devices discovered within this research are included where possible, as all are able to produce electricity even although their main purpose may have been to fulfil other functions.

2.2.1 Technological review

One initial task set within this overall research was to identify the various forms of tidal and wave technology and to provide a detailed evaluation of current and emerging technology. A stand alone report was produced which provides a more in-depth analysis of the industry and technology past, present and possible future, which cannot

be incorporated within this thesis because of page and word constraints. However an electronic copy has been included within the accompanying DVD data which is explained at *Appendix K*.

The technological review in itself can be used as a current reference on MEC technology. The review has already been updated several times since the initial review was completed early in the research. Behind the review the technical data were captured in the relational database that is used by the model.

The majority of the material contained is directly from specifications and literature released by developers. Significantly crucial information may be kept confidential and the data (notably surrounding output and economics) in many instances have not been verified by a third party.

The review therefore incorporates both wave and tidal technology and includes 76 devices, with a further 30 having been identified and logged in the main database, however for reasons relating to insufficient technical data these are not processed by the model. As a break down there are 45 wave devices and 31 tidal, with a further 24 wave and 6 tidal identified but not presently used. With insufficient data this is not a major concern as when the data do become available then they can obviously be included. Historical device designs were also researched as part of the review, and added to the database for completeness. It is also worth noting that the model may actually find a historical design theoretically suitable at a given site. A full list of all the devices included within this research is given in *Appendix I*.

One of the main conclusions from a previous springboard study was additional sites may have been considered feasible, and better matching criteria may have been identified, if additional forms of technology were reviewed (Wemyss, 2004). With this in mind, it was deemed essential that the review included a broad view of past, current, and emerging technology.

2.2.2 Wave energy and devices

Existing wave power devices can be categorised by several different methods: the design used to harvest energy from the wave, the size and orientation, the intended

location, and by the power take off. The intended location includes shoreline and offshore, both of which were covered in this research. The offshore category can then be broken into two further sections: nearshore, and *true* offshore where a device would extract energy from the wave in deep water around ≥ 50 m. The reasons for the differing locations are described later in more detail.

If the size of device is very small compared to the typical wavelength, the device is described as a point absorber according to a device's horizontal size and orientation. Conversely, if the extension is comparable to, or larger than the typical wavelength, the device is called a line absorber, with the descriptive terms terminator and attenuator being more frequently used. A device is described as a terminator or attenuator if it is aligned along or normal to the prevailing direction of wave crests respectively (Brooke 2003).

Designs that attenuate the wave may be classified in various ways, for instance: oscillatory motion, type of absorber, and type of reaction point. Energy can be absorbed by the heave (vertical motion), surge (horizontal motion in the direction of wave travel), pitch (angular motion about the wave crest), yaw (angular motion about a vertical axis), or combinations of these.

The conversion of wave energy to usable power relies, in all cases on the effect of the wave's force on some material or fluid, be that a moveable mechanism or for instance air or hydraulic oil. Three fundamental approaches can be set out from this within which all wave energy devices fall:

- Water to air interface. By allowing the wave action to enter a hollow structure (which has an air chamber above a movable body of water) the wave forces the air to move through an air turbine. The turbine then drives an electrical generator.
- Water action on movable bodies. The wave action causes heaving, yawing, surging and/or pitching motion of a solid or flexible body (or linked bodies). This motion acts on a pump, forcing fluid through a hydraulic turbine or motor.
- Water storage method. Waves are channelled along a tapered waterway where sea water is lifted into a confined basin (reservoir) above the normal sea level. The water is then released back to the sea in a controlled sluiceway through low head hydro-electric turbines.

Power take off systems are required as a secondary conversion and are almost always required to obtain useful form of energy. Methods include hydraulic rams and various hydraulic and pneumatic components. Typically, secondary energy conversion is obtained by means of a turbine. In addition, electric generators are included if the absorbed wave energy is to be converted into electricity (Brooke, 2003). An example of how PTO systems work together is the operation of the Aquamarine Oyster. Oyster's hinged flap, pitches backwards and forwards in the nearshore waves. The movement of the flap drives two hydraulic pistons which push high pressure water onshore via a subsea pipeline to drive a conventional hydro-electric turbine (Aquamarine, 2012).

2.2.3 Wave devices coastal (fixed) methods

Devices that are fixed to, or embedded in the shoreline have a major advantage in that maintenance and installation is much less complicated. In addition they do not require deep water moorings and long lengths of underwater electrical cable to the shore.

However, these devices experience a much less powerful wave regime. The reason for this can be explained by studying the behaviour of a wave as it comes ashore. In short, water particles within a deep water wave move in diminishing orbital paths to a depth of approximately $\frac{1}{2}$ the wavelength below the still water level (Duxbury & Duxbury, 1993). Therefore, the radius of the orbit reduces exponentially with depth and as an approximation, 95% of the energy is contained in the top $\frac{1}{4}$ wavelength of sea depth. By the time waves come ashore they have already lost the majority of their energy due to the interaction with the seabed as the water depth decreases.

This interaction occurs as the water depth decreases, this causes the particle motion to change and frictional resistance to appear. The wave forms slow down and become shorter, higher and steeper. The waves break when the steepness reaches $\frac{1}{7}$. This usually occurs when the water depth is around 1.3 times the wave height. Therefore, most of the energy contained within the wave is released in the surf zone when the swell reaches shallow water (Open University, 1999).

This means there are very few sites around the world where coastal forms of wave extraction can take place. The main criteria for an onshore coastal method is for deep water up to the shoreline, or a shoreline that can be modified or used to build an

extraction method. There are of course many cliff sites that will have deep water close to the shore but it is then extremely difficult to house the extraction technology that is required to convert the energy. Another method is to create an environment that can house a conversion method, such as a harbour breakwater.

2.2.4 Wave devices offshore methods

The greatest wave resource is offshore before the wave interacts with the seabed and shoreline. Offshore methods can be categorised into two distinct classifications: nearshore and offshore.

The offshore class of device exploits the more powerful wave regimes available in deep water (≥ 50 m depth) before energy dissipation mechanisms have had a significant effect. Nearshore devices will be placed between the shoreline (but not fixed to) and anything up to the 50 m contour (Brooke, 2003). There does not appear to be a clearly defined distinction for when nearshore and offshore meet. In recent projects there has been an indication by developers to install in water depths of around 70 m. This can be seen with the new EMEC wave berth at Billia Croo, Orkney, and other projects such as the Aegir project in Shetland, both of which are aiming for 70 m water depth (EMEC 2012, 2) (Aegir Wave Power, 2012).

Although the majority of the resource is offshore in deep water there are many good reasons for choosing fixed coastal methods if a site exists, mainly due to the survivability the device. Near and offshore wave devices have to operate in an environment much more severe than fixed coastal devices. In order to extract energy from the waves, the devices will need to be at, or near, the surface where the energy is most abundant. Many devices are floating and require complicated and vulnerable flexible moorings and electrical transmission cables (Brooke, 2003).

As there are limited sites available for coastal methods, offshore technology is being developed in order to make large scale wave energy extraction become a reality.

2.2.5 Tidal energy and technology

Since the earliest days of seafaring and oceanography, it has been recognised that there are strong sea currents with large amounts of energy. These are mainly caused by the rise and fall of tides under the influence of the relative motion of the earth, moon and sun's gravitational fields. Useful energy has been extracted from the flow of water currents for centuries, mainly in the form of water wheels or tide mills in rivers and estuaries. A tide mill consisted of a pond filled through a sluice during the flood tide and emptied on the ebb tide via an undershot water wheel. In more recent times tidal barrage schemes using the same principle (to store water behind a barrage and thereby storing potential energy) have been constructed.

Tide mills were in use around the coasts of Spain, France and the UK As early as 1100. La Range Estuary was used as a Tidal Mill from the 12th Century and the Schelde River in Belgium was also used around 1800. They remained in common use for many centuries, but were gradually replaced by more convenient methods of power generation. The power was typically used for grinding grains into flour, the last working mill in the UK (Woodbridge) was closed in 1957 after over 800 years of service. Power was available for about two to three hours, twice a day. In Hayle, England, tidal power was used to “dredge” a shipping channel by flushing it regularly with a pulse of stored tidally impounded water (World Energy Council (WEC), 2001).

Tidal mill and barrage schemes use the height difference between high and low tide, however, the flow of tidal currents can also be harnessed to generate power using current turbines and hydraulic devices. Tidal energy (unlike most other forms of renewable energy) can be predicted with high accuracy and the energy available for conversion can be forecast with confidence.

2.2.6 Tidal barrage technology

Tidal barrage technology is a proven concept with the first (and still the largest) example of a large commercial tidal barrage being the La Rance barrage on the Rance estuary in Brittany, France. Construction began in 1961 and was completed in 1966. The 22 km² basin has a tidal range of 13.5 m (equinox tide) and the barrage across the basin is 750 m long providing the towns of Dinard and St Malo with a major road

connection, thus saving a 35 km drive. The 24 x 5.4 m diameter turbines (rated at 10 MW each) can generate power during the flood and ebb cycle giving an overall rating of 240 MW. Annually La Rance produces around 600 GWh (EDF, 2010).

The smallest commercial tidal plant is located at Kislaya Guba on the White Sea in Russia. It has a 500 kW capacity. There are approximately 10 other small barrages scattered throughout the world, but they are not intended for commercial power generation. For example, there is a 200 kW tidal barrage on the River Tawe in Swansea Bay, that operates the gates of a lock. China has several tidal barrages of 400 kW and less in size.

The second largest commercial scale tidal barrage was put in service at Annapolis Royale, Nova Scotia, Canada in 1982. Annapolis utilises the sea water of the Bay of Fundy home of the world's highest tides which can reach 17 m in height (World Energy Council, 2001). Similar barrage schemes have been proposed in the UK at the Severn Estuary (with a mean spring tidal range of 12 m) and Mersey estuary (with a mean spring tidal range of 8 m).

A barrage scheme for the production of electricity at the Severn Estuary has been investigated as early as 1925 with the establishment of a dedicated study group. In 1975 the Central Electricity Generating Board (CEGB) published a study stating a barrage would not be feasible unless the energy situation deteriorated significantly (Peters, 2010). In 1979 with the energy crisis the barrage was reinvestigated by the Severn Barrage Committee which resulted in an energy paper recommending a 10 mile barrage between Brean Down and Lavernock Point (HMSO, 1981). This proposal was investigated further by the Severn Tidal Power Group and in 1989 it was estimated the barrage would cost £8 billion (generating 17 TWh of electricity per year) and was not considered economically viable given the then present energy situation (HMSO, 1989). The barrage was cited within the 2003 UK Government Energy White Paper as a future possibility, although not considered fruitful to pursue at that stage (DECC, 2003, 2). In 2007 DECC through the Sustainable Development Commission concluded the project could play a key part of the UK meeting its 2020 and 2050 CO₂ emission targets (DECC, 2011, 2).

At the beginning of the millennium detailed plans were emerging for the construction of various tidal barrage plants in Korea, mainly the Shiwa (254 MW), Garolim (480 MW) and Incheon (1 GW). Reports on the progress of these projects vary, although it is evident the Shiwa project has been underway for some time as the original compound was built for flood mitigation and agricultural purposes (Lee *et al.*, 2006). An exact completion date is unclear for the project as many target completion dates can be found, most of which have passed. In circulation there are also planned completion dates of 2012 and 2015 for the Garolim and Incheon projects respectively (Korea Herald, 2010).

A barrage scheme can also forge a transport link across an estuary, which is beneficial for the socio-economic environment. It also has the advantage of having a long operational life with low maintenance costs, which can lower the economics of the electricity production. However, large tidal barrage schemes do have major drawbacks. Expensive initial civil engineering works are required which are usually lengthy, with significant environmental consequences experienced in the estuary. These consequences include:

- Poor water quality.
- Variations to water levels and, therefore, the inter tidal zones.
- Disturbance to habitats and their ecology.
- Violent sluice and turbine currents causing altered sediment distribution and erosion.

During construction, major environmental impacts can also occur, for example, La Rance Estuary was isolated from the open sea for 3 years during construction. There are also a very limited number of sites around the world where large tidal barrages can be constructed due to tidal conditions and geography. Various tidal barrage studies have estimated that as little as 20 sites world wide may exist for large scale barrage schemes (Hammonds, 1993). It is for all of the above reasons, tidal barrage technology was not considered any further within this research.

2.2.7 Tidal lagoon technology

An alternative to tidal barrage technology is tidal lagoons, a new approach to offshore tidal power generation that helps resolve some of the environmental and economic

problems associated with tidal barrage technology. Tidal lagoons use an impoundment structure and low-head hydroelectric generating equipment situated offshore in a high tidal range area. Shallow tidal flats having been identified as the most economical sites.

Although an alternative to tidal barrage technology, it is still likened to this method for various reasons. This is mainly due to workings and construction of tidal lagoons. They both suffer from one common drawback in that a substantial amount of capital has to be available, i.e. major engineering has to be carried out before any output is gained. However, rather than blocking an estuary with a barrage, offshore tidal power generators use an impoundment structure, making it completely self-contained and independent of the shoreline, thereby eliminating the environmental problems associated with blocking off and changing the shoreline. Although an offshore hazard is created, navigation is not prevented and from an environmental point of view concerns such as migratory fish will not be affected by isolated offshore structures.

Considering tidal lagoon technology is in a very early stage (in contrast to the maturing tidal stream technology) the method was not considered any further within this research, although a robust model would be able to determine suitable sites in the future with more detailed information.

2.2.8 Tidal current technology

The kinetic energy within tidal currents can readily be harnessed with more simple engineering concepts than compared to tidal barrage technology. Tidal currents usually have a low velocity, however, when these movements are channelled through constraining topography, such as straits between islands, shallows between the open sea, and around the ends of headland, the tidal velocity is increased.

Probably one of the biggest milestones in tidal power was the realisation that turbines (similar to that of designs to work in air) would work in water. The main advantage of this, is that tidal development was able to move forward quickly using experience already gained in the now more mature wind sector. It is for this reason many devices resemble underwater turbines, with a few exceptions.

Although tidal devices operate in a relatively stable location the environment is still technically challenging. Any mechanical device does not generally like to be exposed to seawater, and electrical equipment is (by its nature) averse to moisture. The high density of water (around 832 times denser than air) means that devices are exposed to large forces acting on their structures from both the movement of the tides and the effects of surface waves, especially if surface piercing. By definition, they also must be installed in areas where high current velocities are present, where tidal windows (slack water) are very short, contributing to difficult installation and maintenance operations.

2.2.9 Description of relevant devices used in modelling

The technological review describes all the identified wave and tidal devices in full. There is also a discussion document detailing an alternative categorisation method of these devices in terms of their marine placement. These documents are located within the “Write up and associated files\Technological Review” folder on DVD disc 1.

To save the reader referring to the technological review within the DVD, a summary of the devices relevant in this thesis are described below. These are the devices that are important to the modelling results later in the thesis.

Wave Dragon

Wave Dragon is an offshore wave device that has a large reservoir contained within the structure. This reservoir is filled by waves overtopping the structure, channelled by 2 wave reflectors towards a ramp where the water is elevated and released at the base of the structure via turbines. The device is buoyant and is tethered to the seabed. The device is referenced in the model as Device 4.

Pelamis

Pelamis is an offshore wave device which consists of four long cylindrical sections linked together by three hinged joints containing three hydraulic independent power conversion units. The device is tethered to the seabed, is buoyant and floats on the surface where the relative motion of the different segments of the device, as it contours the surface, provides the power. The device is referenced in the model as Device 5.

OSPREY

The OSPREY (Ocean Swell Powered Renewable Energy) design is a nearshore wave device. The power take off system is an Oscillating Water Column (OWC) housed in the buoyant device that is ballasted to create a gravity base on seabed. The device is referenced in the model as Device 7.

Wave Star

The Wave Star is a nearshore wave device based on a row of floats, with integrated arms, which are fixed to a horizontal shaft with a one way bearing. The device is held on station by the structure penetrating the seabed. The device is referenced in the model as Device 13.

PowerBuoy

PowerBuoy is a nearshore wave device that uses an internal piston that moves as the buoy heaves with the rise and fall of the waves, and in turn driving a seabed generator. The device is buoyant and tethered to seabed. The device is referenced in the model as Device 26.

Marine Current Turbine

The Marine Current Turbine (MCT) is a tidal stream device using a pair of axial flow rotor turbines. The nacelle (with turbines, gearboxes and generators) is mounted on a monopole that penetrates the seabed. The device is referenced in the model as Device 46.

TidE1

The TidE1 is tidal stream device using a pair of contra-rotating turbines mounted together on a single crossbeam. The nacelle contains the gearbox and generator. The turbines are of an axial flow rotor design with an assembly which is buoyant and is fixed (submerged) to the seabed using a flexible wire mooring arrangement. The device is referenced in the model as Device 47.

Hammerfest Strøm

The Hammerfest Strøm is a tidal stream device. The nacelle contains the gearbox and generator. The turbines are of an axial flow rotor design. The bottom mounted base is a steel structure with gravity footings made. The device is referenced in the model as Device 56.

Tidal Generation Ltd

The Tidal Generation is a tidal stream device. The nacelle contains the gearbox and generator. The turbines are of an axial flow rotor design. The bottom mounted base is a steel structure with gravity footings made. The device is referenced in the model as Device 64.

Test wave device and test tidal device.

The test wave and tidal devices are set within the model to have favourable attributes to allow the model to be tested. As for design they are assumed to use an Oscillating water column (test wave) and water turbine (test tidal). The devices are referenced in the model as Device 75 and Device 76 respectively.

ID	Name	Type	Depth	Resource	Distance	Output
4	Wave Dragon	Wave	30 m	48 kW/m	Null	11 MW
5	Pelamis	Wave	50 m	27 kW/m	5 km	0.75 MW
7	OSPREY	Wave	14 m	25 kW/m	0.3 km	2 MW
13	Wave Star	Wave	15-20 m	10 kW/m	Null	5 MW
26	PowerBuoy	Wave	30 m	Null	Null	0.02 MW
46	Marine Current Turbines	Tidal	50 m	2.83 ms ⁻¹	Null	1.2 MW
47	TidE1	Tidal	30-200 m	2.57 ms ⁻¹	Null	1 MW
56	Hammerfest Strøm	Tidal	Null	1.8 ms ⁻¹	Null	0.35 MW
64	Tidal Generation Ltd	Tidal	20-100 m	Null	Null	1 MW
75	Test wave	Wave	5-200 m	27 kW/m	100 km	1 MW
76	Test Tidal	Tidal	5-200 m	2 ms ⁻¹	30 km	1 MW

Figure 2.6 showing a summary of devices that feature in the data modelling and analysis later in the thesis. These parameters within the database are key to the calculations of the model. Values that are unknown (Null) will not allow the model to consider the devices beyond the initial stages of testing. The reason these devices do feature in the more detailed modelling is because these values are updated in the model testing in Chapter 5 of the thesis.

CHAPTER 3 – DATA REQUIREMENTS AND MODEL DESIGN

This chapter describes in detail the design and data requirements of the model, and is structured to reflect the sequence of steps undertaken:

- Initially a generic dataset review was conducted to identify the data required to construct a model to satisfy the aims of the research, (3.1 to 3.3).
- Following the initial data review, a top level model design was developed, (3.4).
- After discussion, a top level design for a working example of the model is presented, recognising there was neither time, nor available data to construct the ideal design, (3.5 to 3.6).
- Before a more detailed design could be finalised, a closer look at the available datasets was required to give a clear description of the inputs, outputs, data structures and how all of these interact, (3.7).
- The available datasets identified required manipulation which is documented, (3.8).
- Leading from the full data description and manipulation, a more detailed working model design with the model data flows was developed, (3.9).
- To conclude the chapter, a review of the model testing methodology is documented, (3.10).

At the earliest stage of the design it was envisaged that the project would have data requirements that fall into three distinct forms: 1) External datasets, 2) Self constructed datasets, and 3) Automated model datasets.

3.1 External datasets

The boundary of the project was defined early in the project as a relatively wide area, with coordinates up to 61.5° to 54° north / 9.75° west to 3.375° east. Considering this geographical range and the time scale that was involved, it was impossible to manually construct data for this region, or if so, it would not be at any kind of resolution that would be helpful. Therefore, to save time (and in many respects to increase accuracy) it was deemed essential that data be sought for many of the model parameters.

In the early stages of the project it was difficult to determine exactly what data would be available, however, it was clear the model would require resource data (wave and tide)

and bathymetry data in order to conduct the most basic of site analyses. For more complex and accurate analysis various constraint datasets would be required. An idealised list of datasets (and potential sources) for a definitive site analysis was developed as follows:

- Resource data such as wave, tidal, and wind. Sources: DTI, Seazone.
- Bathymetry. There are various water depth datasets available from various sources such as: International Hydrographic Organization (IHO), UK Hydrographic Office (UKHO), GEBCO, SeaZone, DTI.
- Other physical data such as geological data to confirm the condition of the seabed and so on. Sources include British Geological Survey (BGS), UK offshore oil and gas information (UKDEAL), SeaZone.
- Areas of high vessel density associated with narrow channels and shipping. Various data sources available: Automatic Identification System (AIS), marine radar and traffic systems.
- Offshore structures such as in the oil and gas industries and their associated pipelines, safety zones and so on. Sources: UKDEAL, SeaZone.
- Offshore electrical and telecommunication cables. Source: UKHO.
- Wrecks and other marine archaeological sites. Source: UKHO.
- Former dumping grounds and contaminated areas. Source: UKHO.
- Military zones such as training areas and bombing ranges. Source: UKHO.
- International shipping lanes and areas of high vessel density. Sources: International Maritime Organization (IMO), AIS.
- Fishing grounds and aquaculture. Sources: Marine Scotland and Crown Estate.
- Offshore wind (various deployments and leasing rounds), and of course other MEC developments. Source: Crown Estate.
- Other activity areas and licencing. Source: Crown Estate.
- Other marine resource extraction such as marine aggregate dredging.
- Areas of high recreational use.
- Protected and special sites, such as: Special Protection Area (SPA), Sites of Special Scientific Interest (SSSI), and Special Areas of Conservation (SAC), National scenic areas, RAMSAR (Convention on wetlands) sites, Marine Nature Reserves (MNR), National and Local Nature Reserves (NNR/LNR). Sources: Crown Estate, Scottish Natural Heritage (SNH), Marine Scotland.

- Areas close to protected sites where the designation includes mobile species such as seals and birds.
- Other environmentally valuable sites (that are not officially designated), such as: maerl beds, reefs and so on.
- Breeding areas for: birds, seals, cetaceans and fish such as herring spawning areas.

3.2 Self constructed datasets

A high percentage of the data that was specific to this project had to be sourced and compiled.

An initial task was to conduct a review of the past and present wave and tidal technology. This allowed the required knowledge of the technology and the industry as a whole to be gained. It also allowed the construction of a database (logging each device) with any known associated data to be used in the program model. For the model to operate effectively, device data (such as the rated output, depth constraints, resource constraints, core construction materials and so on) were all fundamental attributes for the various model algorithms. The devices that are important, in terms of model testing for this thesis, are detailed above at *2.2.9 Description of relevant devices used in modelling*.

After assembling the device dataset from the review, similar datasets began to be produced. These datasets were for: ports, coastal power stations, offshore cable types and so on. These were essential to the project, and although easy to construct with publicly available data, it was a time consuming task.

To source the actual data, various methods were used. Most of the searches would normally start on the Internet which would usually give an indication where information was available. For the port dataset for example, data were obtained from a variety of sources, the port's own information on the Internet and handbooks, Admiralty charts, Google Earth, pilot handbooks, tide tables and atlas. This allowed various data fields to be populated, such as: water depth, quay lengths/locations, tidal ranges and times, maximum ship dimensions, port services and so on. More often than not, each source provided a little piece of the jig saw required to complete a useful dataset.

The self constructed datasets comprise:

- Devices: containing their type, specifications, output, weight, Power Take Off (PTO) type, and cost.
- Power Take of Systems (PTO) and their costs.
- Material types and their costs.
- Mooring types and their costs.
- Cables type: containing their design, specifications, and costs.
- Power stations/electrical landing points: containing thier locations, spare capacities, connection charges.
- Ports: containing their locations, capabilities and cost.
- Ships: their specifications and costs.

3.3 Automated model datasets

The third category of data that is used within the program model was data that were constructed automatically by the program itself. Working with the two other data collection methods described above, the model is designed specifically to have the functionality to construct new datasets from these existing datasets, i.e. perform a set of tests or calculations and print the results to a new dataset. In a cascading effect the newly constructed data are then used again for further analysis, which may produce further datasets, and therefore continuing the data development process. As one example, the program model has to be able to take every given location, calculate the distance to the nearest power station, and store this distance and station id at each location to a new dataset. Then, for any given location, this newly constructed dataset with the distance values is used to calculate a cable type, again storing the results, which are then used to calculate a cable cost and so on. The model produces a substantial amount of data by this method.

When the model program produces a new dataset, it is in the form of a matrix, with the data spatially arranged within the area of the project boundary, and in the same format as the externally sourced data which are then used for comparison and computation. This functionality allows single values such as latitude and longitude in other datasets such as list tables (for example a database table containing only a name of an entity and its location) to be used by the program model to construct distance matrixes to the

spatial boundary of the project. This design methodology allows spatial data to be quickly and easily constructed.

3.4 Top level design for the model with the identified datasets, and project aims

Once the general input datasets had been identified, the top level design for the model was developed. From the identified input files a structural flow chart was constructed to help understand how these datasets interact with one and other, and what parameter values can be determined.

At this stage, the design followed the logic that each process (a labelled text box within a structural flow chart) would carry out a specific task which allows the model to progress, firstly to find a valid site result for each device (to satisfy the site selection aim of the project) and then to a final profit/loss indicator for that site. This design assumes a dataset of devices will sit around the described set of sequences, and therefore each device is tested in sequence (with each process detailed in the flow chart) to determine where it can be located, and give a profit/loss indication for that site.

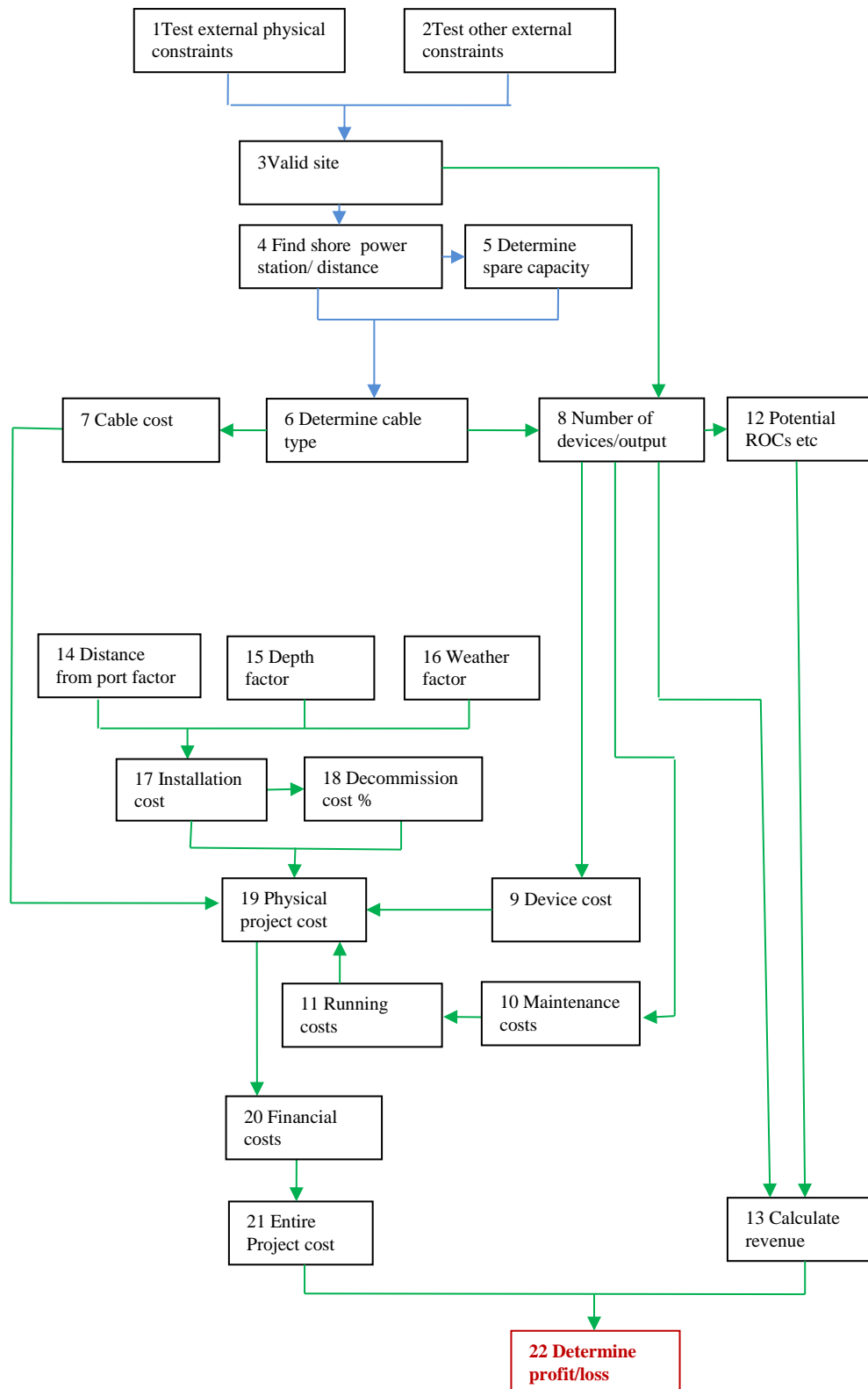


Figure 3.1 showing a top level design for what is required to satisfy the aims of the model. Most of the processes have been simplified (grouped into higher level single processes) for this level of design. The blue arrows represent the site analysis aspect of the design, while the green ones represent economic aspects.

The design (shown in *Figure 3.1*) it not intended to describe how this model works. Furthermore most, if not all, of the above processes require complex code and data structure management to achieve their specific aims, and also require design methodologies at much lower levels from this the top level design. However, in the following text, the top level design is explained and is expanded to show how the lower levels of the model were built up around it.

3.5 Overall description of the program model design

In order to process the considerable amount of data that were required for this project, the most feasible approach was a batch sequential computer program, where the program takes each device in turn, and works matrix cell by cell from the north west boundary (working east) line by line (south) through the external data conducting the various tests required. With this design, the model is able to process every device with every site during the one single program run without any user intervention.

3.5.1 Finding a valid site

It can be seen from *Figure 3.1* that many of the processes are complex, and require multiple calculations to take place.

During the initial processes (indexed 1 and 2 in the flow diagram) the device will have to pass various tests to ensure the device is suitable for the site. There will be many physical tests such as resource, which will restrict all devices if not favourable. After all, no energy converting device can be deployed in an area with no or little resource. There is also an upper limit to this of course where the resource may be too extreme. There will be other restrictions such as shipping or scenic areas that are not so clear, and could be device specific. For example, some devices are on the seabed and others will have structures piercing above the water column. Another potential restriction is the presence of offshore structures such as in the oil & gas industries. For most devices this will be a restriction, however a very small number of devices may actually be able to work in conjunction with these structures (for example providing a fixing point in deep water with electrical infrastructure) and would pass this test at this location, where other devices would fail.

Each device will require substantial information to be known in order for a valid site (index 3 on the flow chart in *Figure 3.1*) to be found. In fact, the list is determined by the number of external datasets that can be obtained or constructed. Therefore, the processes and associated datasets required to undertake the physical constraints test (index 1) use the following design format:

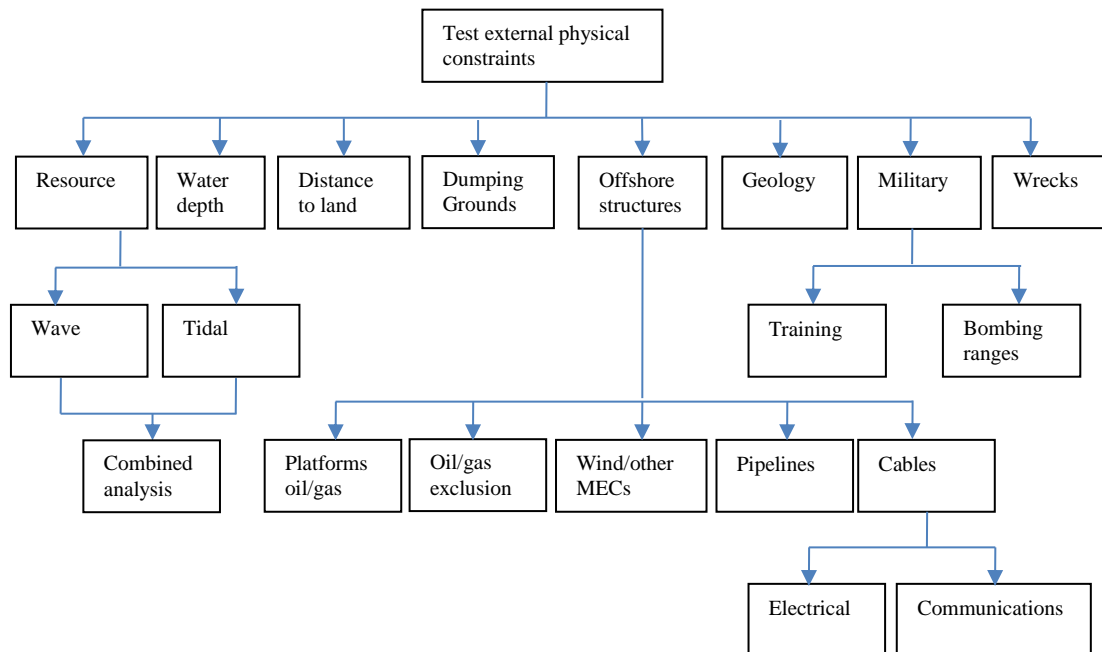


Figure 3.2 showing an expanded view of the likely physical constraints (and therefore datasets) that the device is tested against at every site.

For testing other external constraints (or non physical external constraints, at index 2 of the flow diagram) a very similar method was applied with various additional constraint datasets being used:

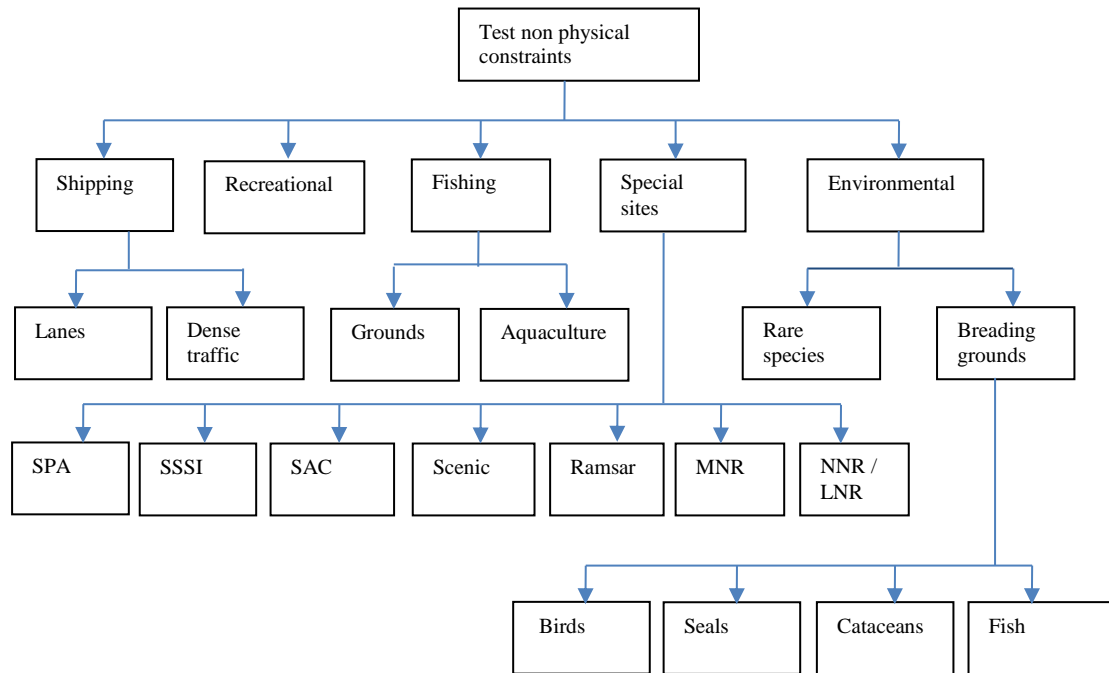


Figure 3.3 showing an expanded view of the non physical constraints (and therefore datasets) that the device is tested against at every site.

Many of the main dataset headings have been expanded (*Figure 3.3*) as each dataset category has numerous associated sub datasets which require individual processing. It is not possible to obtain generic (or national) datasets with all the information required for this large study area. It is beneficial in any case to process datasets at the lowest specific levels, as it is then apparent where exactly the device may be unsuitable for deployment, with the exact reasons why.

The constraints (shown in *Figures 3.2 and 3.3*) are many and varied, which caused difficulties trying to source relevant data, and once obtained, caused more problems in terms of varying resolutions and coverage. Therefore, another design requirement became apparent at this point. The model will have to handle datasets of different types, and also be able to take in new datasets when available, as it became obvious new datasets would become available, and most not within the timescale of this research. There are various ways in which the model will be able to handle new datasets, such as a conversion script to convert data to a common format before being processed by the model, and by identifying the resolution of the input data, the model logic can also work to this specific resolution at run time.

For the model design when more than one valid site is found, there is then the need to compare the adjacent sites as they may have a hydrodynamic effect on one another. That is, a decision will have to be taken as to how many devices will be allowed at any particular site. For example, when a tidal device is placed downstream of another device (which of course becomes upstream once the tide has turned) each device will experience a modified resource. The downstream resource will be less as some of the energy has already been converted by the upstream device(s) and the structure shape and operation is likely to cause turbulence in the water column. For wave energy this is similar with offshore devices likely to affect devices between the further offshore deployments and the shoreline. Again, this is likely to be a reduced (and distorted quality of the) resource.

Therefore, multiple valid sites need to be analysed to determine the effect of spatial placement, and sites (along with the total allowed number of devices at any given site) may need to be reduced if they are deemed to potentially cause a problem. There is little known about the possible effects of multiple devices in close proximity, as to date deployment of device arrays has not been achieved. There can however be estimations drawn from similar studies, such as Wind Park Effect for the spatial distribution of wind arrays.

The results of such calculations will feed into the economic calculations of the model (index 8 on the flow chart in *Figure 3.1*) in terms of how many devices will be placed at a site, and therefore the site output. At this point a suitable load factor for each device will be determined. This value (in megawatt hours MWh) will have to take into consideration the individual device design load factors with the largely unknown packing densities, so will be initially set low in order not to over estimate. A key feature at this point is the ability of the design for these values to be calculated more accurately in the future, by using key user defined variables in the database, as knowledge is gained. There is a further discussion of packing densities at *Appendix A.8 Calculate the number of devices required and device output at a given site.*

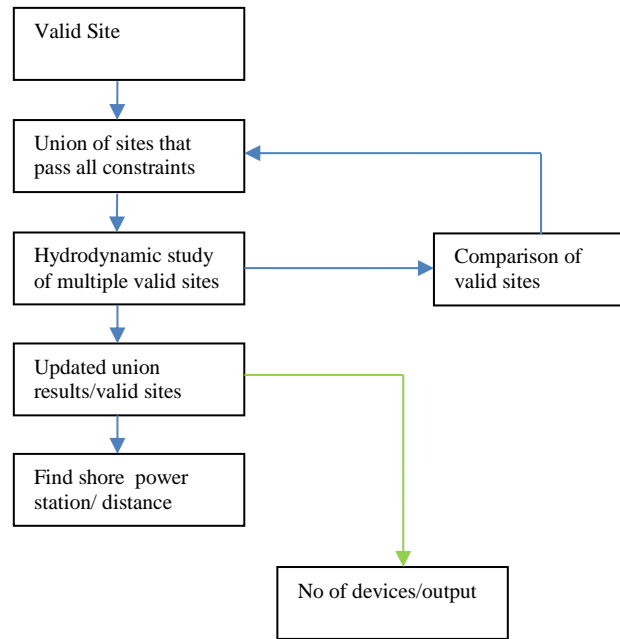


Figure 3.4 showing an expanded view of the more detailed site analysis incorporating a hydrodynamic modelling element.

The above can only be achieved by incorporating a hydrodynamic model to determine if certain sites will cause a problem, which may in turn modify the number of valid sites, i.e. potentially more sites eliminated as the model essentially creates another constraint to be overcome. The reason this hydrodynamic consideration is incorporated separately from the other constraints (that is, the hydrodynamic analysis is not an extra constraint test carried out at the same time as the other constraint analysis) is because the entire valid sites dataset has to be completed first. Valid sites have to be found so a comparison can take place. This cannot be done during the constraints analysis, as this increments one site at a time and the overall valid sites (index 3 in *Figure 3.1*) is only complete at the end of the constraints batch procedure, meaning combined valid site analysis can only take place after all the valid sites have been found. To help the logical operation of the model, the resource datasets would likely be altered by the hydrodynamic feature at run time for each device each time a valid site was found.

3.5.2 Determine a cable, costs and revenue

Once the valid site (index 3) is found, the model determines the closest land power station/power landfall point. This is done by comparing the location of each site, and the location of each recorded landfall point in a separate dataset, which also holds the

spare grid capacity of this landfall point (covering indexes 4 and 5 on the main flow chart). If this landfall point does not have enough capacity (which maybe for various reasons, such as bottle necks exporting the energy on land, Beaulieu-Denny in the North of Scotland for example) the next closest landfall point has to be found. Storing (and testing) data such as power landfall points without any capacity, is as important for the working of the model as landfall points with capacity, as it may be able to show where bottle necks are, and therefore where development is required. Another way to look at this would be to say, what if we entered a “landfall” connection point in the required dataset to be somewhere offshore, i.e. in an area where there are currently only long and expensive distances to shore facilities. The model would then be able to test this connection point which may positively affect the amount of available sites, and would most certainly change the economics of these sites and therefore the overall spatial distribution.

It is clear the model has to be setup in such a way where connection points and/or associated capacity values can be changed to show any distribution changes. It was therefore a design requirement that as many values used by the model for calculations could be altered for the purpose of analysis.

Knowing the spare capacity and distance to landfall allows a cable type to be determined, index 6. There is a significant amount of logic required for cable selection, with a further dataset containing the various cable types depending on distance, and rating. Distance is assumed to be a key variable for the selection of cable type, with various configurations having an ideal minimum and maximum range that is used to test against the distance to landfall point. The database has a cable configuration example from the offshore wind industry, this has been used to define a working range which may not give a true reflection for some MEC development scenarios. However this range can be changed by the user as knowledge is gained. Once the single ideal cable type (with associated rating) is determined by the model the number of devices (assisted by the valid site analysis at index 3), the output of the site (and therefore overall revenue via any potential financial incentives) as well as the cable and connection costs can be determined, which covers indexes 8, 9, 12 and 13 of the main flow chart.

To determine the device cost (index 7) more information on what makes up the device is required. The base materials, power take off (PTO), and moorings need to be

considered. These are often largely unknown figures, however the model has to be able to cater for these values so they can be estimated and/or added as this knowledge is gained and/or better understood. The above three entities that contribute to the device cost, also require maintenance (index 10), which will obviously differ depending on the various systems. For example, steel structures will need maintained on a more regular basis than concrete. These with the running costs (index 11), which includes other such attributes such as manning, contribute to the physical project cost (index 19).

At this point knowing the cable and device costs, we can also determine a total project asset value. This combined with the running costs and the revenue generated can be used to carry out discounted cash flow analysis on the overall project. The approach described here is summarised in *Figure 3.5*.

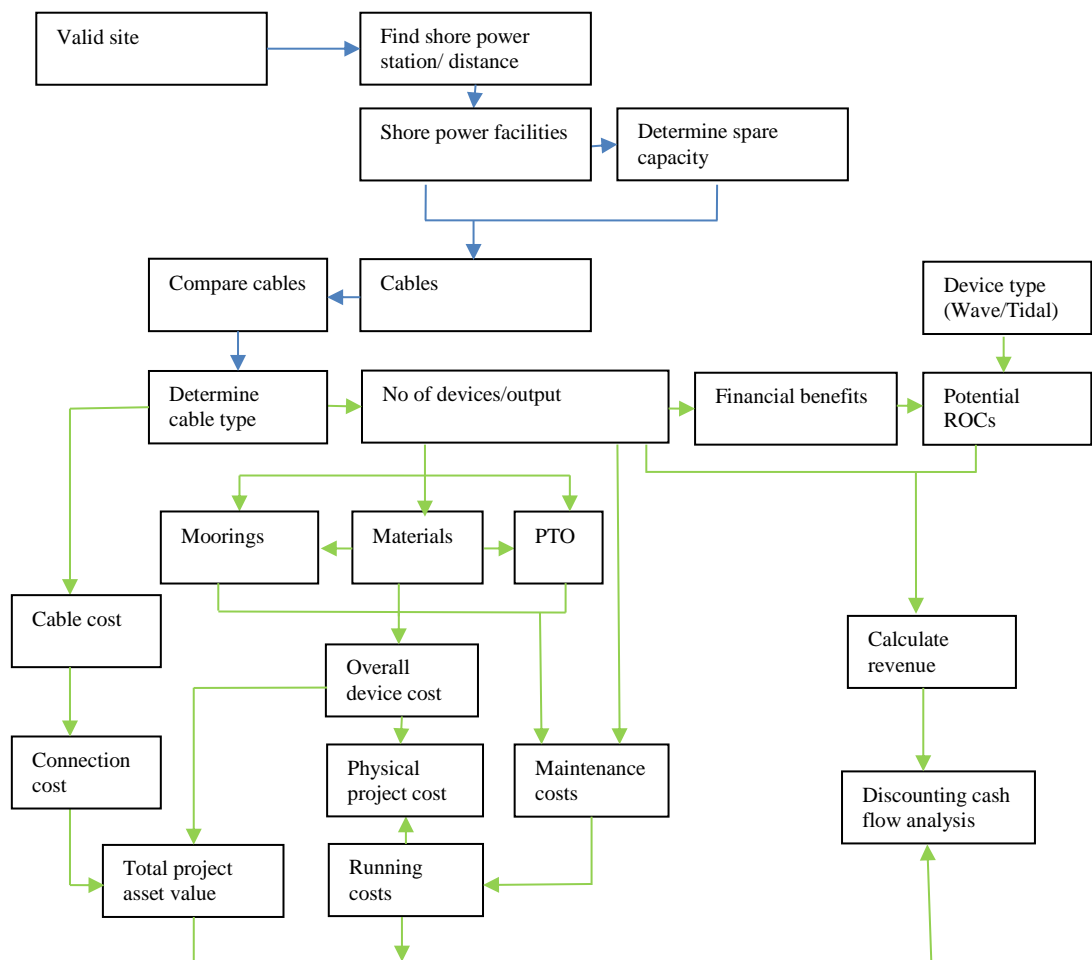


Figure 3.5 showing an expanded view of how the cable, various costs and revenue are determined.

The detailed low level design and code for this section is substantial.

3.5.3 Determine installation, decommissioning and financial costs

The design work described in 3.5.1 and 3.5.2, provide the main foundations of the model. However, a few more details complete the description of the overall design. To complete the physical project cost (index 19), the installation costs (index 17) need to be determined which is another complex problem. One of the main attributes that will determine the installation cost for any particular devices is the geology of the site in which the device will be deployed. The geological dataset can be referenced back through the hierarchy (as it was processed in the site analysis procedures) and will therefore be known by cross referencing. Other factors will include the distance from port, water depth, and weather windows covering indexing 14, 15 and 16 (see *Figure 3.1*) and for each particular area the shipping costs. The distance from port calculations work in an identical fashion to determining electrical landing points, so that computer code is reused at this point. The water depth is already known as it has been processed during the site analysis.

Weather factoring is slightly more complex and takes into consideration wave and tidal resource at the site, and also wind. Not all sites are as exposed as others so this could have a significant outcome to the overall profit/loss result, as it will have a bearing on the ships and equipment used to carry out the installation, and weather windows for maintenance.

As for decommissioning (index 18) this is another unknown but does work in a similar (reverse) fashion to that of installation, so a percentage figure could be used together with all the previous work described above to give an overall physical project cost, and therefore an overall amount that can be used to calculate the finance (index 20) required. This will in turn then give an entire project cost (index 21) which can be directly compared to the revenue gained (index 13) giving a final profit/loss figure (index 22). This approach is summarised in *Figure 3.6*.

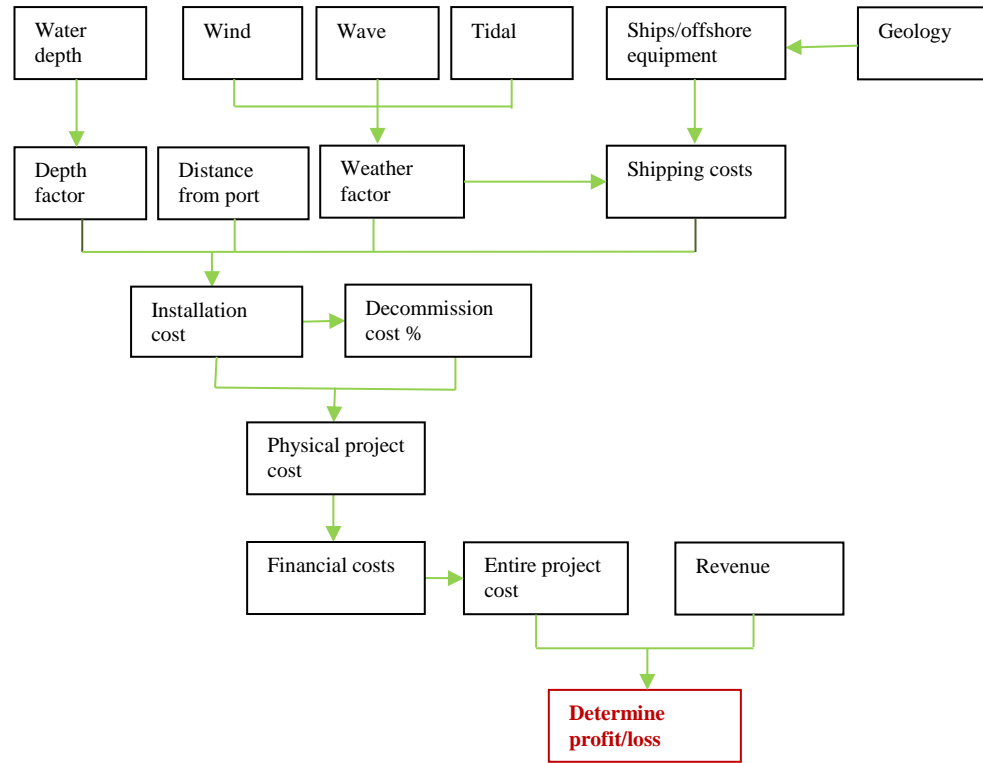


Figure 3.6 showing an expanded view of how the installation, decommissioning, project costs, and profit/loss are determined.

3.5.4 Conclusion drawn from top level design

Given there were many constraints encountered during this work, mainly research time (to source, construct, format the various datasets identified above) and available resource to purchase datasets that cannot be obtained publically, it was considered, at the initial design phase, not possible to construct the model in its entirety. For example to undertake the full valid site analysis, a detailed hydrodynamic model would be a substantial undertaking as there is little knowledge at present on how devices will affect one and other, which is a significant research topic in its own right.

Therefore, the strategy was to concentrate on a working representation of the model, giving the best indication of how the overall structure would work with available time and data. Unfortunately, sacrifices had to be made and it was not easy to decide how best to demonstrate an overall working model from the ideal design described. That is, what was to be built, and what functionality had to remain in the design. As already mentioned, some of this was determined by data availability. However, some aspects

were too important to leave out, regardless of how difficult it proved to obtain the data required.

3.6 Design analysis for working example of model

At this juncture it is worth noting what was left out of the model presented here and why. Starting from the top the model design now only compares a device to: resource, bathymetry and distance to land data, rather than the extensive constraints originally designed. This is for several reasons. The data for all the identified constraints proved difficult to obtain, and to verify the working of the model, logically, not all constraints would be required. For the model design to process three constraints is logically the same as processing a large number. It is also the case that the constraints analysis is one of the less complicated features to add onto the overall program at a later date, as the structure will be in place to import and process the additional constraint data.

From this point, rather than cut out key aspects of the design, the decision was taken to simplify many of the processes. Again, this has been done to show an overall working structure where the level of detail can be built upon at a later date. Therefore, the valid site analysis and installation calculations are simplified, as are the running costs, detailed financial analysis, ROC systems and so on.

After careful consideration a simplified design was reached to show an overall working model from the earlier complete design. That is, an overall working model which would provide a valid site per device and profit/loss indicator for that site, rather than encompassing all aspects of the overall design. The design in *Figure 3.7* details this, with the processes at a design top level; again the lower level functionality is not shown. As before, the design is based on a batch operation, running through each device in turn, with each site, until all devices have been tested with all sites.

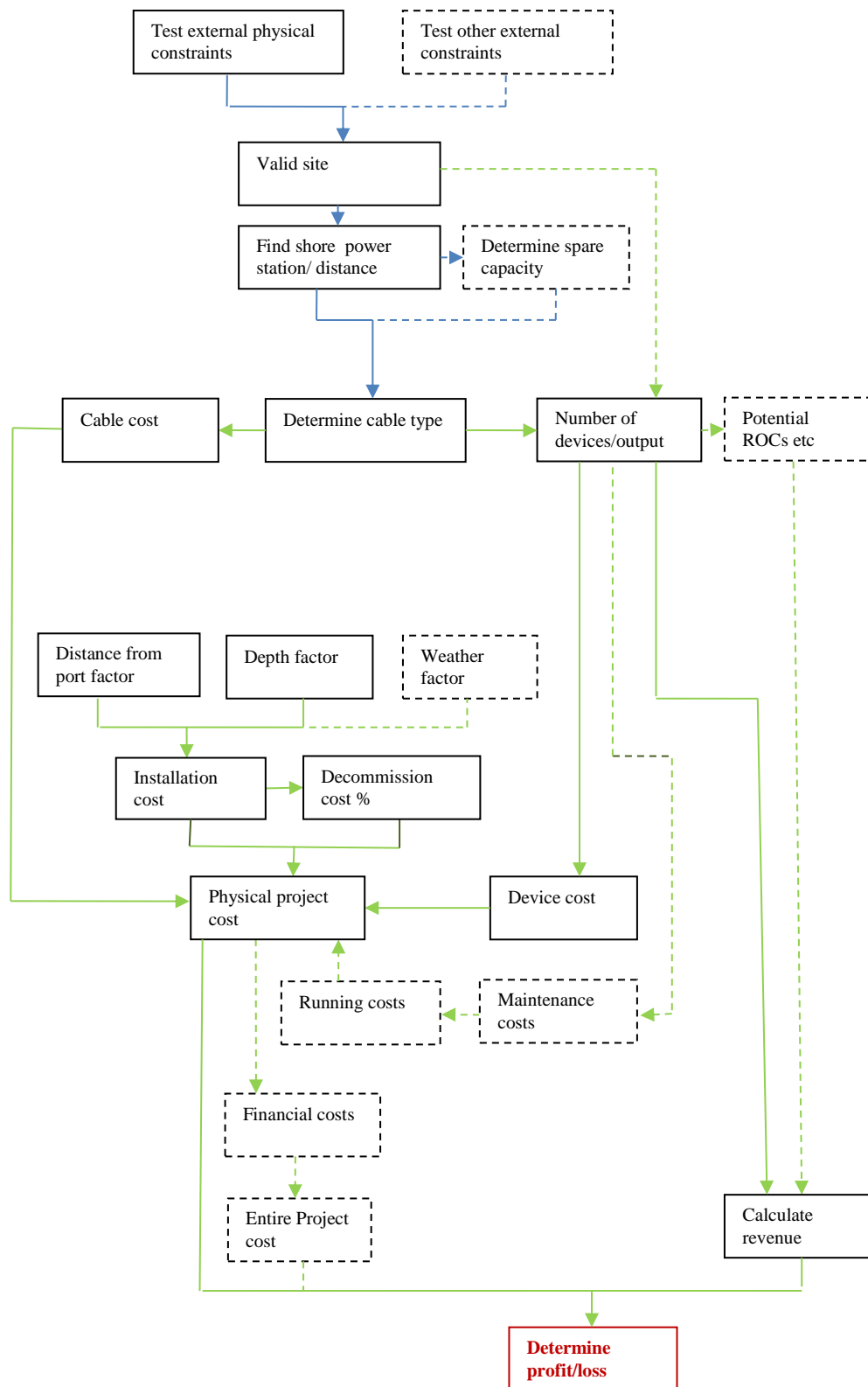


Figure 3.7 Top level design of overall ideal model, with dash sections showing what was omitted from the example model top level design.

Before a more detailed design description of the example model is presented, a closer look at the available datasets (and how these were formatted) allows a clearer indication of the inputs and outputs, data structures and how all of these interact.

3.7 Datasets selected to construct model

The requirements for the three already identified categories of datasets used: external required datasets, self constructed datasets, and automated model datasets are described in more detail.

3.7.1 Acquired external data

The main requirement after the design stage was to begin construction of the model and provide a site analysis from oceanographic features such as the bathymetry, wave and tidal resource. There are various sources where bathymetry data could be obtained for the study area. Obtaining the resource data on the other hand was not so easy, there were many specific studies in localised areas from smaller studies which have been used to build up resource modelling, such as used by the DTI.

The DTI produced an atlas of the UK renewable energy resources in 2004 to document the resource available for wave, tidal and wind energy. The atlas also came with a CD ROM with the underlying data mainly in the database management format of dBase. In terms of this project the data accompanying this work was invaluable as the resource and bathymetry data can be extracted. The dataset gained from this source is listed in full in Appendix A. This list also shows the dataset types and the value range of the data entries. In the DTI CD ROM there are also some other very useful datasets, “distance to shore” being one as various distance calculations were required in the model. There are also 20 wind datasets which could have been used in the installation/decommission costing in the model. However, this was scaled back in order to save time and ultimately allow for a complete representation of the model to be completed. These available datasets is a feature that can easily be added at a later date.

The digital DTI datasets also contained more data than appears graphically in the hard copy of the atlas. Some of these have been used in calculations (for example to

calculate mean results from several underlying datasets) and were therefore not printed in the atlas as stand alone sets.

There was slightly more choice when considering bathymetry data during the initial data review. Publicly available bathymetry data were also acquired from the General Bathymetric Chart of the Oceans (GEBCO) digital atlas. The GEBCO, one minute grid data are freely available to download via a host at the British Oceanographic Data Centre (BODC) (General Bathymetric Chart of the Oceans GEBCO, 2003). Therefore, a copy of the north Atlantic data were obtained which was stored in an xyz format within a text file. After the bathymetry datasets were selected and formatted for the model, it was found that GEBCO had released a higher resolution dataset. This was to a half minute resolution compared to both the approximate 1 minute datasets from the DTI and previous downloaded set from GEBCO.

There is also bathymetric data available from SeaZone who sell digitised data from UK Hydrographic office Admiralty Charts. This is a widely used resource and was considered at the time of the data review. There were several concerns at the time with the SeaZone data in comparison to the data that could be obtained from the DTI/GEBCO.

SeaZone mainly vended data in localised zones, i.e. small geographical areas such as found on shipping charts. To cover the area required the majority of the individual Seazone sets for Scotland would have had to have been purchased. There were also concerns regarding data processing such as joining the various zones to construct a single dataset, and the use of techniques such as kriging to interpolate irregularly spaced Seazone data to a required model grid, i.e. to ensure a populated matrix (at a defined resolution) was made up from the distributed sporadic nature of Admiralty charted depths.

Taking the data resolution discussions further it also became apparent that regardless of the quality of resolution (around half minute resolution) gained by purchasing data, there was a restriction from the resource data in any case. As the DTI resource data were to be used for resource, therefore, potentially higher resolution bathymetry data to run alongside the resource data were not going to enhance the model significantly, that is, in relation to the cost of (and work required to format) the data.

The easy access to the GEBCO and DTI datasets, and the overarching aim of producing a working example rather than a detailed section of the model, meant the SeaZone datasets were not considered further.

As for the GEBCO data it was a similar story with the higher resolution half minute dataset. There was the added disadvantage that this set only became available after the DTI and lower resolution GEBCO datasets, which were selected for further modelling. The GEBCO one minute dataset was the first dataset found with the initial data review and after going through the various formatting processes it was decided to include the GEBCO data alongside the DTI bathymetry data for two main reasons.

- The two datasets (at slightly different resolutions described fully within sections 3.8.1 and 3.8.2) can be used to validate one and other.
- One of the main design requirements is to develop a model that can handle data at different resolutions. Therefore, the GEBCO data (in comparison to the DTI data) will be used to test (and be an example) of how the model data structures are built to handle this functionality.

3.7.2 Self constructed datasets review

For the self constructed datasets there has been little change with the model redesign. All of the main datasets captured (with the exception of ships) are still used within the model. However, some of the attributes within some of the main datasets are redundant. The flexibility of the model to pick and choose the data to manipulate, allowing additional data to be incorporated at a later stage, is maintained.

3.7.3 Automated model data

The third category of data used within the program is the data that are constructed automatically by the program model itself. Therefore the new design and changed outputs to the overall model will have little effect on these data structures, but with reduced inputs there is proportionately less automated data produced.

3.8 Manipulation of available datasets

Once it had been established which datasets were to be used in the model, investigation focussed on how these datasets were handled. Obviously there are various sources and types of datasets, which required specific manipulation. All of the external datasets were manipulated by various methods (sometimes several times) to enable storage in a format that the program model could use.

The external datasets are obviously constructed by someone (or by a program designed to produce a desired format by someone) and therefore required an initial analysis to identify what this format was. Once the format was understood, the choice was then either to construct program code to directly use the data in its original format, or construct new code to reformat the data into a structure more appropriate to the overall requirements.

3.8.1 *GEBCO data*

The GEBCO dataset was the first external dataset which was acquired. The initial file was in a 1 minute resolution from 90° north to 90° south / 180° west to 180° east which is the entire globe. The original file was 280 megabytes (mb) making it difficult to work with, i.e. simple tasks such as opening the file was difficult. This task was made more difficult in that the original file format was a UNIX Operating System variant where there were various hidden characters that Windows could not decipher.

Therefore, a Visual Basic for Applications (VBA) script within MS Excel was constructed to copy the contents of the file into another file recognised by MS Windows. A further script was constructed to take only the data range required, and again save this to a new file. The resulting file contained data from 65° north to 54° north / 20° west to 4° east, as at this early stage of working the exact project boundaries had not yet been fixed. The project boundaries were later defined once the DTI renewable resource data were obtained.

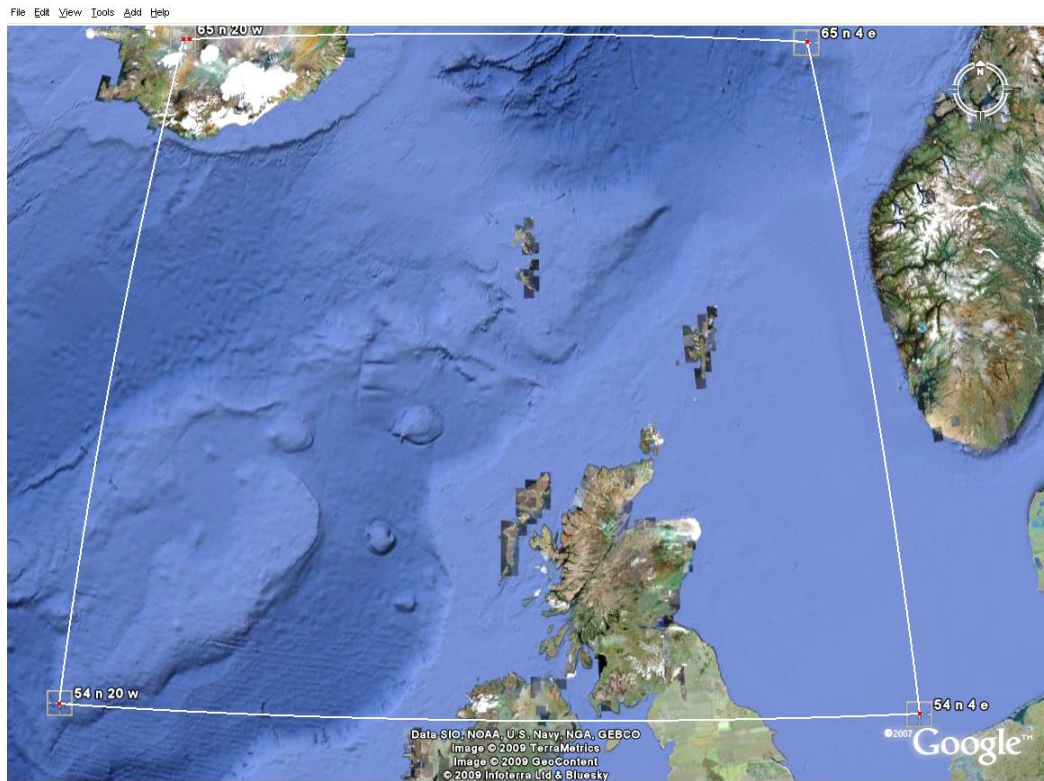


Figure 3.8 showing the boundary of the truncated GEBCO dataset.

The data format of the file was an xyz list format, i.e. location in longitude (x) and latitude (y), and water/land depth/height (z). A further script was constructed to arrange the data (water or land, depth or height) into a matrix format, without the geographic location details, i.e. a matrix containing only the water or land, depth or height. For this dataset, the boundary coordinates and the resolution are known, and therefore there was no need to save the location of each data field against each value, as the location coordinates can be calculated (and therefore referenced) from within the program code by these key features.

The result of the above data manipulation was a VBA constructed sequential file access data file, in the form of a matrix contained 1441 entries from west to east (columns) and 661 entries from north to south (rows) making 952,501 individual data entries.

Sequential data files can only be read from the start of the file, sequentially until the end of the file is reached. This is a very slow and inefficient method when trying to read data from within a file, as to find a given field, the whole file has to be processed from the first entry until the last, regardless of where this field is actually stored within the file. A more efficient way to do this is to use the random access file access format

which VB provides for. The GEBCO dataset was not the only dataset that was considered for the random access format, and the majority of data files during the model development ended up utilising this format. The manipulation required for random access files is detailed in *3.8.4 random access file format*.

3.8.2 DTI data

The DTI data are stored in a database format called dBase. Since the model was at this stage being trialled with MS Excel (which includes a built in version of VBA) it was decided to import the data into Microsoft's dBase equivalent, which is MS Access. Access provides this functionality, and the various tables within the dBase database were successfully imported to Access.

This allowed direct access to the underlying data which was used by the DTI to construct the renewable resource atlas. The aim at this point was to convert the DTI data into the same format as the GEBCO data. The original DTI tidal data covered the area from coordinates: 63.83° north to 48.16° north / 9.91° west to 3.39° east. Therefore, these data covers the UK continental shelf and Channel Island territorial sea limit. The data were at a lower resolution than that of the GEBCO data: 60 data fields for 1° north to south, and only 40 for west to east. This varying resolution is accepted as being a relatively equal resolution between longitude and latitude due to spherical geometry. Although the resolution was different from the GEBGO data, the earlier scripts that were constructed (to follow the same process to obtain the data into a random access matrix) were still used to carry out the same task. This was possible due to script construction relying on variable loop structures, incrementing according to user defined values (i.e. the data resolution) rather than static code that had to work to a fixed data resolution. The decision was taken to leave the DTI data at the original resolution rather than converting either the DTI or GEBCO sets and would be handled by logic in the model which is discussed later in the thesis.

The DTI data was exported from MS Access into a text file format using an export query. This started with the tidal data and the format of each tidal data file was in the form of: record ID number, latitude, longitude and the relevant data value (categories such as spring tidal power density, neap tidal power density and so on) in a list format.

Therefore, a matrix was required for each of the data values within this list, which was undertaken in the programming language R.

The DTI data in this list did not contain a full set of values, due to the study area not being the shape of a matrix, but representing the Exclusive Economic Zone (EEZ) with a list of plot values following the actual shape of the EEZ. At the west, east, north, and south boundaries there would be large gaps when constructing the data in the shape of a matrix. Locations not listed in the DTI set (the locations required to construct a matrix) were filled with blank values when processed at this stage.

These fillers were set to “NA” as this could not be confused with any real data value. The DTI data also did not have any data for land masses so landmass areas were also set to “NA”.

The size of the tidal resolution grid also changed for the outer reaches of the data, to the inner more important areas, resource wise. Where this grid changes offshore, there are also changes in the recorded data where power figures for example are not included. This was again expected as the tidal stream effects are weak in these areas. Therefore, the DTI tidal data were truncated to only include the areas of complete data, which was a significant step to determining the overall study area of the research.

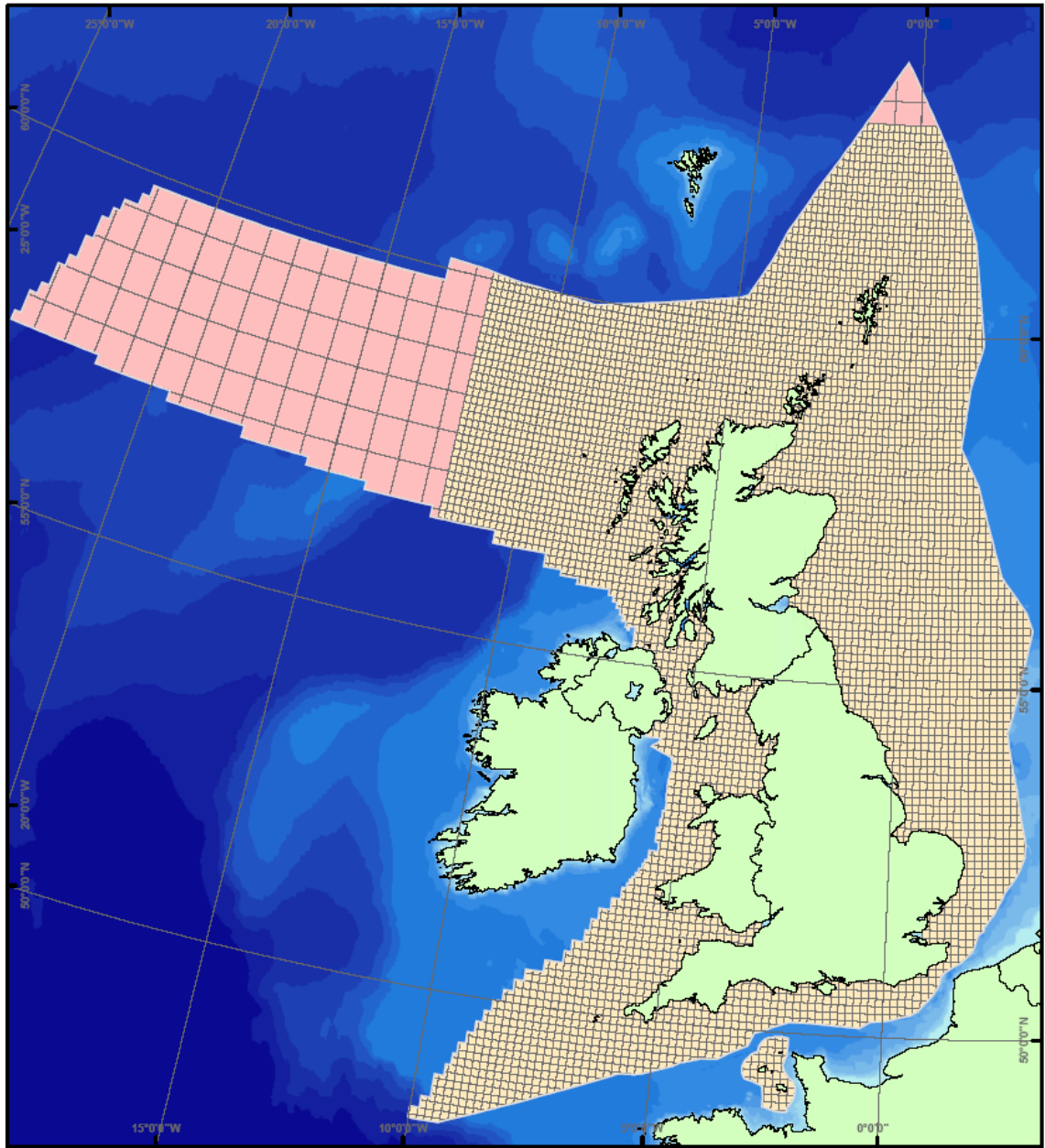


Figure 3.9 showing an example of the boundaries and data resolution changes for the DTI datasets.

The result of this process using R, was a sequential file access matrix, containing just the data values, like the GEBCO data. As before, and using the same methods, the data were then converted into a random access format.

The procedure for the wave data were slightly more complex in that the resolution changed considerably between spatial sections of the study area, with the resolution being much lower in various areas than with the tidal data. The resource for offshore wave sites is unlikely to change in vast open areas so a lower resolution is sufficient.

With tidal sites on the other hand a finer resolution is required in order to highlight areas of resource that can change significantly within a short distance.

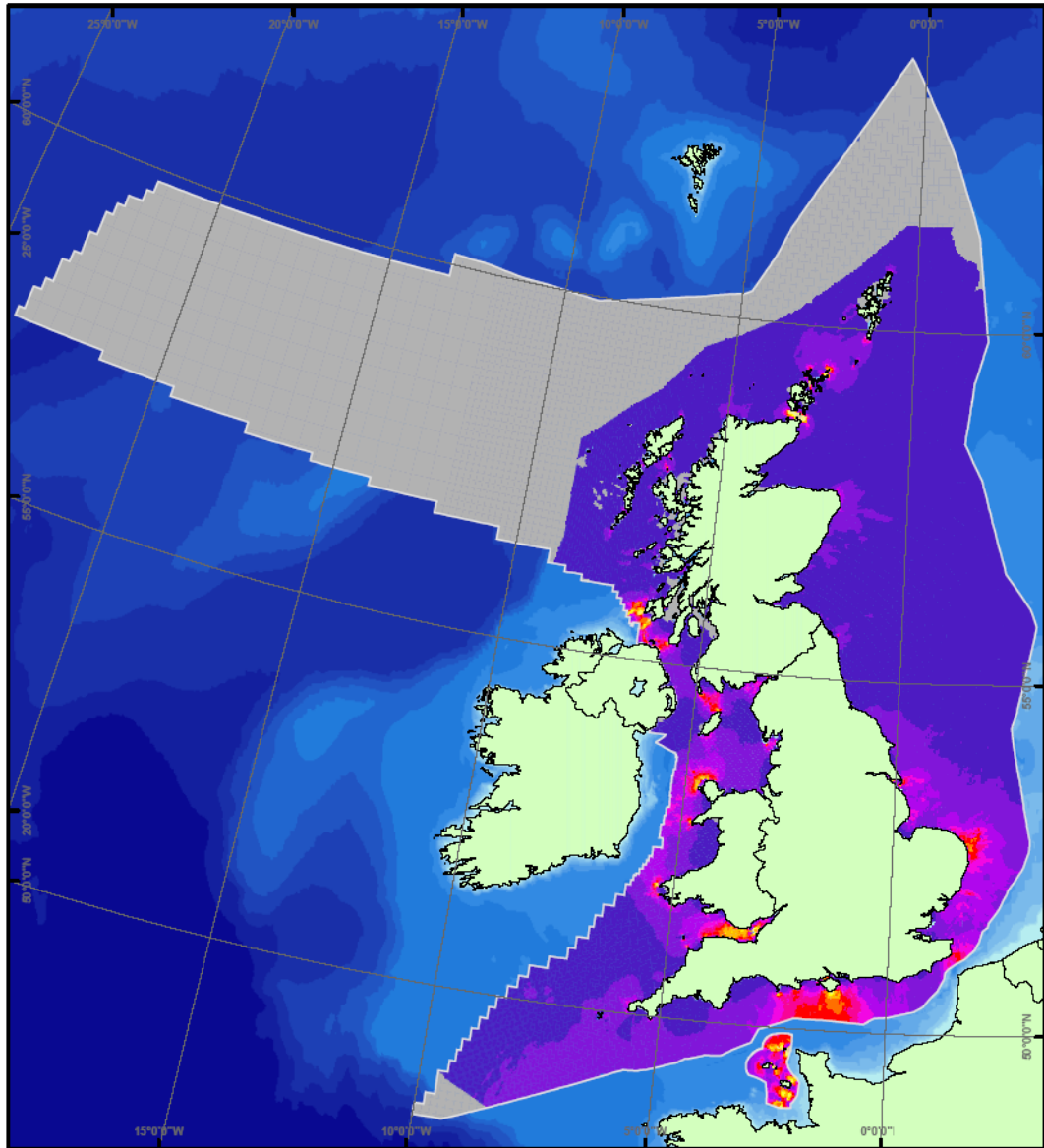


Figure 3.10 showing the annual mean tidal power density, more importantly it shows the boundaries where the main tidal values exist, i.e. areas not in grey.

An R script was then used to produce a dataset of wave values at the resolution of the desired tidal data range, by matching a matrix grid to the size and resolution of the tidal grid, and filling in the fields with the nearest valid wave resource value. A kriging method was considered at this point, however, with the actual data values being so sparse in several areas, it was deemed that no clear benefit would be obtained by using this method.

As with the tidal data, it was also found that the wave data located in areas around the continental shelf (where the resolution became much less detailed) was of little use when considering future site analysis. Also, the tidal data beyond roughly 8° west, had sparse data recorded which is expected due to the nature of tidal resources only having any real significant resource close to land. Therefore, to keep the data consistent over the study area, the initial tidal matrix (that contained the complete set of tidal resource values) was used to define the project boundaries at this point.

As already stated, the study is focused on the general boundary area of Scottish waters. The DTI data covers the whole of the UK Continental Shelf and Channel Isles territorial sea limit. The western boundary of the data are truncated, which is a feature that could have been used to eliminate the data for the southern part of the UK. However, since the western boundary was set to keep the tidal and wave data consistent it was felt that it would be a good option to leave the southern datasets, as this would be beneficial if the scope of the model were to cover the entire UK and Channel Isles in the future, and, again this highlights the flexibility of the model design. With random access format only the relevant data needs to be read by the program code. Therefore, extra data can exist within the datasets without causing any problem to the adopted boundary design. The southern data remains within these datasets, however, it is not read or processed by the model.

The resulting DTI matrices contained 520 entries from west to east (columns) and 785 entries from north to south (rows) making 408,200 individual data entries. However, for the project boundary adopted, only 520 columns and 450 rows (resulting in 234,000 entries) are used within the program model. This resulted in the data matrix spanning 61° 29.5' north to 53° 59.5' north / 9° 35.25' west to 3° 23.25' east, which is an area that extends over the southern Scottish border to ensure a good coverage of the south of Scotland.

3.8.3 Self constructed and automated data

Since the structure of both data methods were controlled directly from the outset, or by a program script written to do so, there was no real need to manipulate any of these datasets. The export of several datasets from different formats such as MS Excel to

Access was a straightforward task, unlike the procedures described above with the external datasets.

The self constructed datasets were initially stored within MS Excel spreadsheets as the initial versions of the model program used Excel as a platform. However, as later versions were progressed, the need for a more coherent programming platform led to the use of Visual Basic (VB) and the various self constructed datasets were transferred to MS Access.

MS Access is also an environment that suits the structure of the self constructed data. These sets are not large matrix files containing data values for a single entity (such as bathymetry or resource) rather, they are lists, features or facilities (such as a device or a commercial port) which have numerous attributes assigned to them.

During the collection of data to make up these datasets, more data were recorded than completely necessary, outwith the physical boundaries of the project. There were several reasons for doing this, for example, the methodology for the cabling function had to include a larger dataset of power stations/connection points. The most obvious power stations/connection may exist just outside the current boundary, which would obviously affect the results. The power station/connection point dataset was also used as a test example of the flexibility of the model, i.e. to show how the model could operate with a dataset larger than required and still give the desired result. Therefore, the decision was made to include all UK and Ireland power stations and landing points to show how additional data can exist without causing any operational problems when running the model. Other connection points, such as Norway and Faroe, could have been added considering some of the sites may be closer to these areas than to the UK. Future modelling (to that conducted for this thesis) can be undertaken by adding these entries to the power station/connection dataset.

91 power station and connection points were identified, 60 of which are outwith the actual study area. If (for example) the boundary of the research was extended to include the entire UK, these datasets are already in place. No redesign of the actual model logic needs to take place in order for data within these datasets to be included or excluded. This also applies to the insertion of additional power stations/connection points within the existing dataset.

The methodology behind the data capture of ports (structure and storage) was similar to that of the power stations and connection points. However, the same logic for working through an entire UK and Ireland dataset was not used for ports. This is because the power stations/connection points were captured and processed as an example of how this can be done and not affect the operation of the model. The ports dataset processing on the other hand just covers the study area and slightly beyond. However in the future if the model were to include a larger area then additional data can be processed, as within the port dataset there are entries for ports around the boundary of the study area which includes England, Ireland, Norway, Denmark, Isle of Man and Faroe, totalling 450 additional ports. These ports could be added to a model run in the future to see if their addition, changes any of the overall results.

3.8 4 Random access file format

As already mentioned above, sequential data files can only be read from the start of the file, sequentially until the end is reached which is an inefficient method. Therefore, with the amount of data and analysis likely to be required there was a preference for the random access file format. This file format in VB/VBA acts like a record structure within the file, where each record (and then column within that record) can be called directly. This method allows each record, and each column within each record to be referenced by a unique index. Any data field can be called directly, like a two dimensional array, or a cell anywhere within an MS Excel spreadsheet. For example, in Excel: `x = sheet1(10, 10)` would make variable x equal to the value stored with row 10 column 10. The random access equivalent to interrogate this location from a file would be `x = dataStructure(10).column(10)`.

Unlike Excel however, data structures do require to be set when reading and writing random access files as the method works by knowing the size of each field, and the number of fields in a record. If a field size is declared and then written at 4 characters in length, it has to be read back into the input structure in exactly the same format. To use this system effectively to its full potential more information has to be known about the data to ensure the data fields within the program data structure are set to the right size, avoiding truncating any values, or wasting storage by potentially over allocating field character (variable) length.

To provide some validation of the various input datasets an additional script was constructed to ascertain and check the physical length of the data values. Thus in a random access data structure, a value "143.3" would require 5 characters to store the information. At the same time, for validation use in later analyses, the largest and smallest values were also saved along with the physical value with the longest length in character terms.

This seemed a long winded when compared to data handling in MS Excel, however, the version used (Office 2000) in the early coding only allowed 256 columns and a maximum of 65536 rows. To have used this would have required splitting the dataset into sections. With subsequent versions of Microsoft Office (2007 and 2010), the maximum number of both columns and rows is much greater, and this would not be a restriction.

The setup of the random access files did require various programming skills as described above, however this was not significant compared with trying to use various "work around solutions" with Excel.

3.9 Working model design

Now that we have described the input dataset formatting, the detailed model design can be presented. To help with this process the design documented in *3.6 Design analysis for working example*, will be used to show the various input and outputs the model utilises.

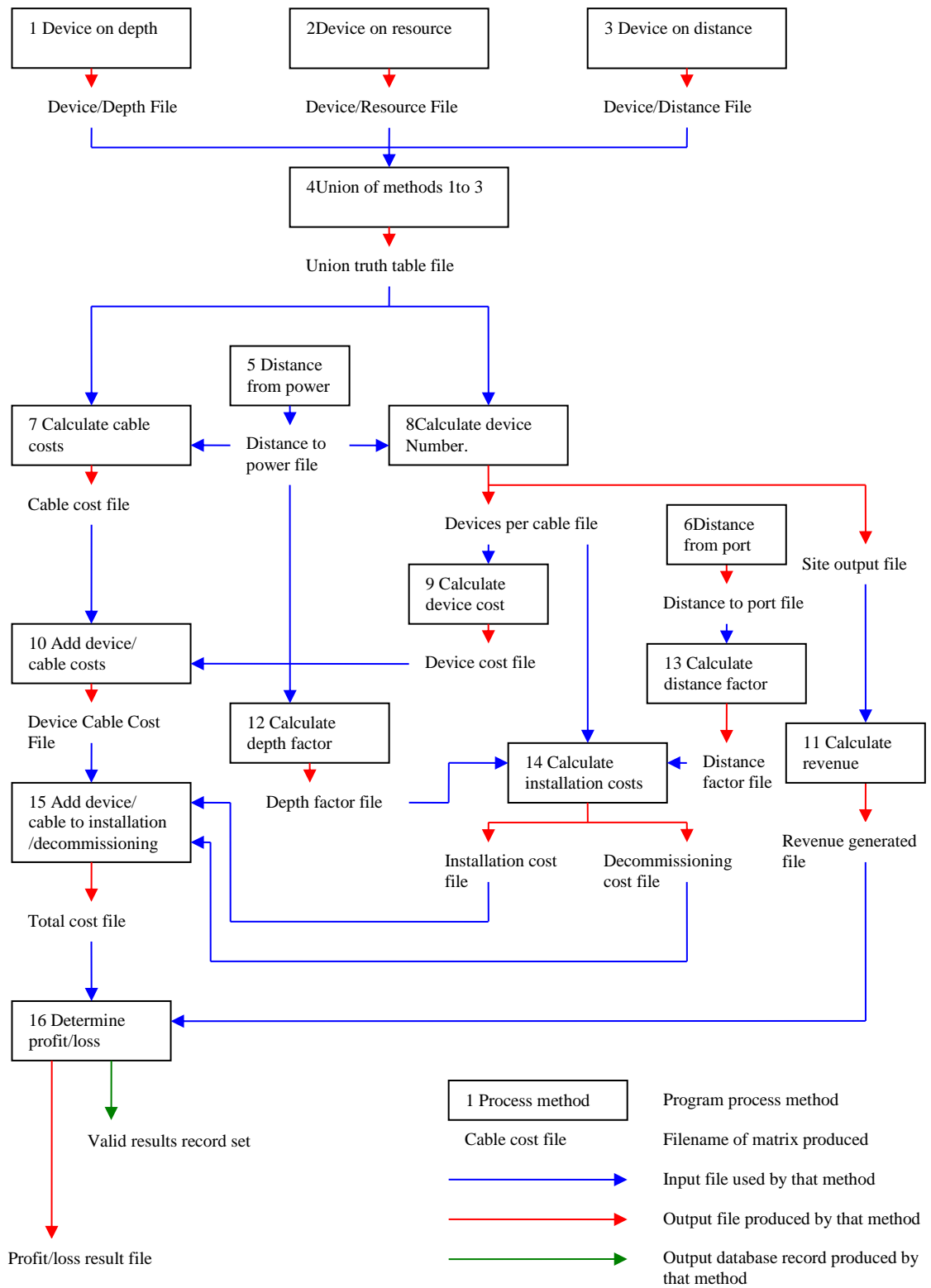


Figure 3.11 example model, top level design. Hierarchical data flow chart of the batch operation's main methods. More emphasis is given in this design to the data flows between the main processes.

This design phase shows the datasets and data flow, many of which are automated and generated by the program. This top level design is showing the processes, with the specific inputs and outputs datasets. The low level design is described below.

3.9.1 Low level design of model construction

The low level design of the model was a significant undertaking as would be expected for a project this size. The as built model has produced a substantial amount of code (approximately 4000 lines) which is complex and difficult to describe in a concise manner. Much of the design work for the main body of design, described within the flow chart in *Figure 3.11*, was conducted in pseudo code, a method by which computer scientists use to describe programming code in English without using the syntax of any particular language.

The reference number in the flow chart processes (*Figure 3.11*) is again an index, this time for the full low level design which is fully documented in *Appendix A*. Therefore *Appendix A.1* contains a low level design description for devices on depth from the flow chart above. *Appendix J*, also contains the full pseudo code of main model following the same indexing system.

With the model being essentially one large computer program, it is a large collection of algorithms and calculations. The designs within the appendices take the reader on a step by step description of the design of the various program blocks that make up the model. The model has been designed in such a way that new and extended blocks of code and logic can be added in with ease. Within the code there is documentation indicating where future logic should be added, such as some of the initial features that had to be left out of the working model design. Due to space limitations the descriptions do not include the various scripts used to manipulate the various datasets described at 3.8 *Manipulation of available datasets* although all scripts used are included within the accompanying DVD data.

3.9.2 Low level design of supporting applications and test modules

The program has been written in two sections with a batch and user system sitting on top of the same overall model logic. The batch system takes all the input files, works

through the full set of procedures until all the values have been tested and the relevant results are returned. The second section allows a user to select the values that they wish to be tested and the program then works to these. Although there are two distinct operations within the model application (user and batch) most methods are underpinned by the same logic throughout. The code has been structured in such a fashion so that methods can be accessed from either mode.

The user operation as already mentioned uses the same logic that is used within the batch operation. The batch operation works from the first line of code to the last, the user operation on the other hand works in stages at a time, depending on the user's choice, which is known in computing as "events", and the logic within the user operation is accessed through a Graphical User Interface (GUI).

Unlike the batch process, where each file stored is processed one after the other until the end, the user operation is designed to take a user defined location which is then converted into a row and column location allowing a call to the relevant data within the various files and datasets.

There is also slightly more functionality within the user operation in order to allow the user to see (and therefore understand) what restrictions the system uses to pass or fail data "tests", i.e. they can alter key parameters at run time to allow a test to pass that would normally fail within the batch operation. This extra functionality has meant separate methods to contain what is essentially the same logic was required for the user operation. The design of the user methods are described fully in *Appendix B algorithms and calculations required for model user operation*.

There are also other sections of the program that are required to initialise variables, data structures and datasets which are required by both modes of the application. The design of these are fully described at *Appendix C global algorithms and calculations required for global operations*.

When the model was under construction a random access test facility was developed in order to help test the various random access files, and therefore the model as a whole. The facility was then built into the model as it still acts as a useful function in its own right, and will also be beneficial if future data are added. The facility is essentially an

extension of the batch operation, and the design is fully described in *Appendix D algorithms and calculations required for random access test facility*.

As part of the batch operation there is also a useful extension to the functionality with a facility to display the results from any of the batch output files, i.e. any of the device overall profit/loss results can be loaded up. The design for this facility is fully described at *Appendix E algorithms and calculations used for display results facility*.

There are also many other methods within the program model carrying out various windows events, code sequence, and data loading functions. These methods are secondary to the calculations required to make the model work, and carry out window's GUI tasks to make the applications required to run the model. These methods are required for the application and most are carrying out small tasks with as little as one line of code. Some on the other hand are more substantial and the most important of these have been documented. For completeness of the design, all significant windows and event driven functions are fully described at *Appendix F other windows related methods and functions*.

All the methods in the project have specifically been designed in small manageable sections usually dealing with only one or two objectives. The batch functions use output files as a method to store results, so future functions can use these values in future calculations as mentioned in the top level design phases. The methodology of the user operation of the program is to use internal variables that are passed between functions as the storage method, and hence the reason for various windows methods required to transfer and manipulate these values.

3.10 Dataset design and methodology for testing

There was a considerable effort required to ensure the logic and syntax of the code was functioning as designed. In computing science there are various methods and tools used to help the testing process, as, when the number of lines of code becomes significant, it can become a difficult task. To physically check every single line operation, of which many are in nested loops, would be an impossible task without help of testing methods.

3.10.1 White and black box testing

The most widely accepted methods in computer science for testing software development are white and black box testing, which in essence, are two contrasting testing methodologies. The theory behind black box testing is that the system is tested only by the results/outputs of the system, and if the results match what the code was designed to do, then the system passes the test. The output is checked against the input without checking what happened in between, i.e. inside the black box.

White box testing on the other hand acknowledges that the black box methodology is not fool proof due to: code getting the correct result (by a method not actually intended) and/or an incomplete black box test data strategy. Therefore, the code is looked at more closely step by step to ensure the results gained are not by accident. The output of each input is checked at each stage of the program (box) and therefore is transparent. In practice, both methods have to be used in a software project of this size, and it is also good practice to be aware of the principles and benefits of each.

Black box testing on the model took place after each section or module of code was completed. The model has been built up from a collection of small code sections which is deliberate, as this way it is easy to construct, document and therefore understand and test. Each small section of code was tested with the range of inputs that it would have to handle, to ensure the output was correct. Many of the larger sections within the model were built up from smaller sections dealing with single tasks and, more often than not, stand alone. For example, a stand alone water depth program was constructed where the depth was returned for a given location, which now sits within the overall structure of the entire program. Another example was the initial construction of a stand alone simple cable model which was the first modelling undertaken in the project. The construction and use of these smaller stand alone units allowed for this specific logic to be white box tested before it was incorporated with the larger model.

Black box testing also took place when using the system. Many software developers will test a system by simply using it over a period of time. This is true of this project as the system has been in testing usage ever since the earliest level of functionality, which tested what was already developed, and any interaction of new code. The user and batch systems were used to test each other as they use the same logic embedded in

separate code. In addition, during the whole development, entire potential results were written to separate output files at selected intermediate points, so that they could be independently checked.

With some of the model results, an external method sometimes had to be sought to verify the results. For example, the model has a distance calculation method which measures the straight line distance between two points. The results from the module (when in development) appeared to be what the design had intended, however to be totally confident validation methods such as Admiralty Charts and Google Earth were used.

White box testing was a method used more during the actual software development. During the coding, small sections (sometimes as small as a single line) were tested to ensure they were operating as intended. White box testing is very time consuming and in many ways is a method to help development as much as test it. White box testing was also prominent in discovering logical errors during development. Various methods were used in these occasions, such as the VB variable watcher (where a watch can be placed on a variable so you can see when it changes and what the value changes to), break point (where the program can be stopped at a particular point and continued one line at a time with the watch facility) and outputting values to file or screen while the code was in execution mode.

3.10.2 In built test facility random access files

As part of the functionality of the system, there is an inbuilt test facility for the random access files. This allows any column and/or row to be selected and the data value in that location is returned to the user. For all the static input files (for example the DTI files) and the random access files that were produced by the program, a drop down box is provided on the GUI where the file can be selected. Although this function is now a useable tool within the application, it was initially setup as a testing method while the system was being developed.

3.10.3 Twin application operation

The application, as already described, was developed in two separate functionality modes, described further in *Chapter 4*. One side of the system (user operation) allows the user to select a location which will display a list of all the input dataset values (DTI, GEBCO and so on) for that location. The user then has the facility to select further options (such as selecting a device) and so on. In contrast the other mode of operation takes all the datasets and runs through a batch process. What is important here is that the two very different aspects of the system use the same logical methods and in many instances the same code. Therefore, the first mode was used as testing tool (although its end use was always going to part of the system's functionality) for the overall system, i.e. the batch operation.

3.10.4 Other datasets and datasets produced due to the program design

At times during the development there were opportunities to produce output files containing data that would confirm the logic used on methods, or data in other datasets. For example, there is a method that can calculate the distance between two points that did require a level of refinement to account for the spherical geometry over the study area. A DTI dataset containing a distance value to the nearest land mass was also available. The results from the specific project built calculation method (which allowed batch processes to output files of desired points to point) was compared to the DTI dataset as a method of testing, and as a method to validate the DTI data. Also, the user operation aspect of the overall application shows the result of the inbuilt distance calculations alongside the DTI data result so they can be compared directly. These values generally correlate and the differences are discussed later in the thesis.

3.10.5 VRML (Virtual Reality Modelling Language) data handling

VRML is a virtual reality modelling language where objects can be viewed in 3 dimensions. Within the language there is a facility called an elevation grid where a 2 dimensional matrix can be defined containing elevation values. The 2 dimensional matrix plots the (Y axis), west east (X axis) boundary with the elevation values contained shown on the Z axis (Ames *et al.*, 1997). The elevation function requires the

resolution of the data contained within the matrix, and once this is defined, data such as the GEBCO bathymetry can be displayed in a 3D representation.

This was carried out with the geographical data (such as the DTI and GEBCO data) in order to visually inspect the various datasets. Obviously with the above datasets, if the various data manipulations were successful then the image shown in 3D would represent a 3D map of the study area, which was confirmed.

This was a useful exercise as it helped quickly validate data that had undergone various formatting processes. The original dBase files (the original DTI data format) were converted into MS Access, processed by R into a matrix format and converted into random access format. VRML itself does not work with random access files so several random access files were converted back to sequential, then processed by VRML to visualise the data, example shown in Figure 3.12. These additional facilities also provided confirmation that the conversions to and from random access format were correct.

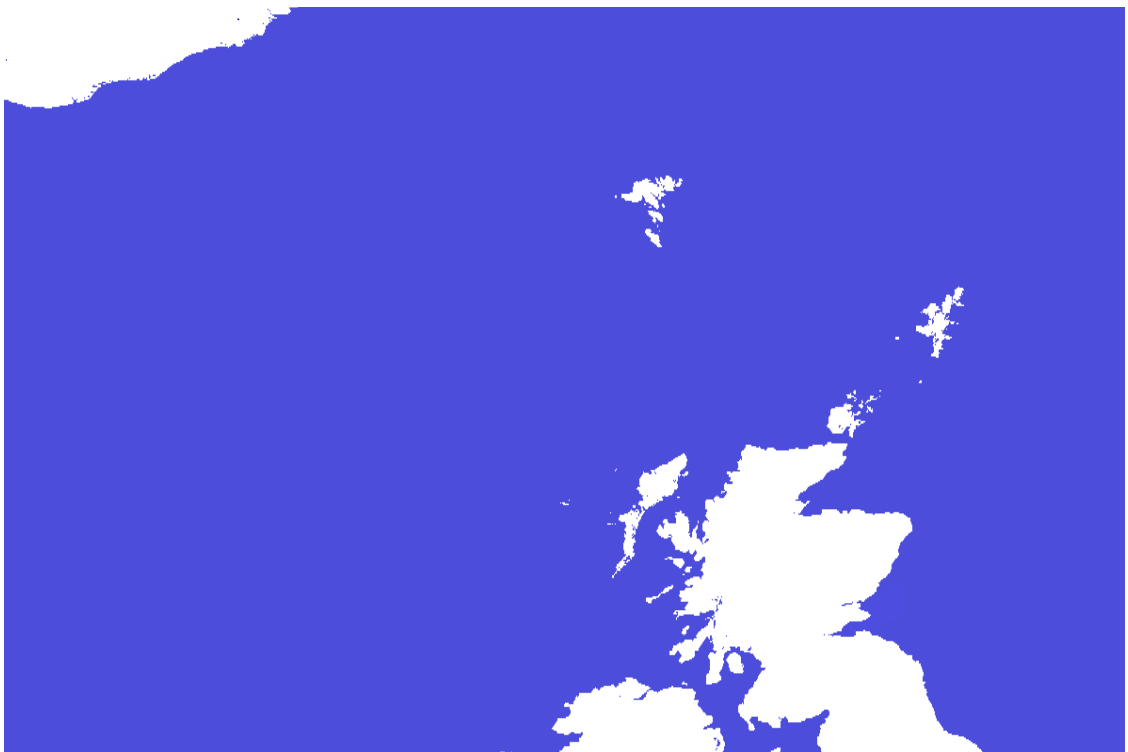


Figure 3.12 showing a VRML image of the GEBCO Bathymetry data viewed from an elevated viewpoint to essentially show a 2D representation of the study area. Data in VRML can be viewed in 3D in graphical viewer i.e. effectively the data at any point can

be navigated to by the user. The above image is in a looking down view of the dataset to represent a map with a flat layer added at sea level.

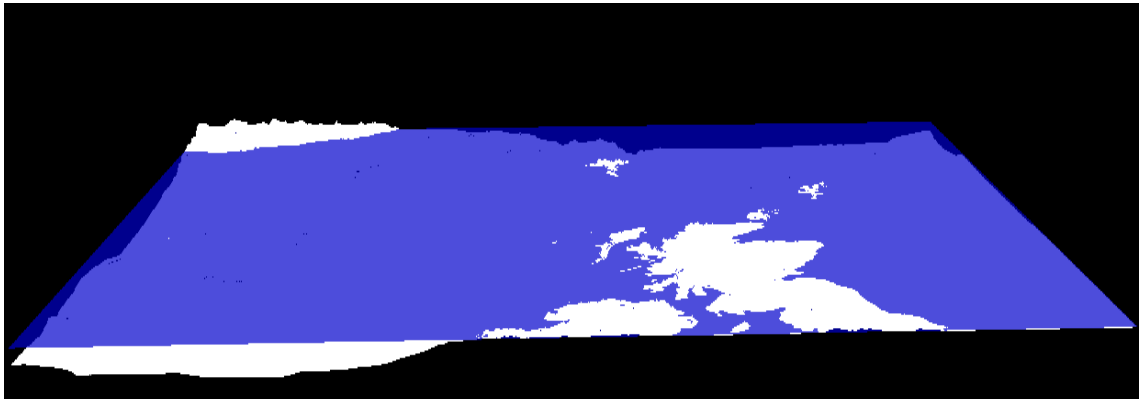


Figure 3.13 showing a VRML image of the GEBCO Bathymetry data from an elevated viewpoint rotated on the x axis to show the 3D element of the data, i.e. white above sea level is land, and seabed below. West of Ireland the data shows a greater distance between the flat sea level blue layer, and the bottom white layer, which represents the descending water depth from the continental shelf.

3.10.6 Other tools such a Google Earth

As mentioned earlier, there were other tools such as Google Earth that were used to verify results, as well as gain data on port facilities and locations etc. The tool was used for many of the port and power stations geographical locations. Google Earth also has a point to point measurement tool which was useful to get a quick result to see if the result produced by the system was within a reasonable error margin. The measurement tool was also able to provide certain port data where the resolution of the image was high enough to measure port facilities such as piers and docks, when their values were not known from other more authoritative sources.

CHAPTER 4 – OPERATION OF MODEL

The logical model has been encapsulated in two separate operating modes to allow greater usability of the package. This package (the overall end product) has been written with a standard Microsoft Windows style Graphical User Interface (GUI) with the Visual Basic (VB) software development tool. The GUI allows the model to be used, without the user having to have any great knowledge of the internal mechanisms that allow the model operate.

This chapter describes in detail the operation of the model, and is structured to reflect the sequence of steps undertaken:

- Introduction to the batch and user (twin) modes of the application, (4.1)
- Full description of the window's graphical user systems, tools and conventions, (4.2).
- Description of batch and user operations and their outputs, (4.3 and 4.3)
- Full illustrated walk through and description of the user operation of model (4.5.1).
- Full illustrated walk through and description of the batch operation of the model (4.5.2).

4.1 Twin modes of operation

The twin operation has been developed to allow the program logic to be utilised in two different forms that enhances functionality and usability. The batch facility works on the methodology that all the available data within the model is processed in a batch process until a set of results is finally achieved.

The user facility on the other hand allows the user to enter a specific location (single matrix cell) and the application package loads the relevant data for that specific location. The user then has various options (such as the available devices for that site) when examining various physical and economic outputs. It is more than possible that the site the user has selected may not allow the user to continue to an overall result, depending on the various validation methods that discount site values, due to properties

not fulfilling a specified criteria. This is also true of various devices at various locations.

The two methods have their specific end use. The batch method is designed to process the data for the entire project area which shows where specific sites and devices can be located. The user facility on the other hand allows a specific site to be studied in more detail allowing the user to view the full details and logical test conditions of the specific site.

The two methods obviously can be used in tandem where the batch system can indicate potential sites that can then be looked at in more detail with the user facility. The converse is also true as if a site fails to show as favourable in the batch results then that site in question can be loaded in the user facility to see what the constraints were. Also, if a favourable site is selected in the user process, the batch process can be run to “see” what adjacent sites are also feasible.

4.2 Graphical User Interface (GUI)

The model started its development under MS Excel working with spreadsheets containing Macro (an embedded Microsoft method to allow more advanced scripts and commands) enabled VBA code. The cells within the spreadsheet were essentially the user interface where various input variables such as the site location, device and so on, were entered into various allocated cells. The embedded code was then activated running an Excel Macro via a drop down menu on the actual MS Excel application, and the various results were returned in various other cells assigned for this output.

A batch list of various inputs was initiated to run which was the full extent of the user/model interaction. With the growing number of datasets and related tests, it became clear a more dynamic platform was required to satisfy the user interaction requirement. Therefore, a user interface was required where the user could select their data choice in a logical manner which then could be processed by the code behind the interface. Within computing science, the sub discipline dealing with user interaction is known as Human Computer Interaction (HCI).

If the main requirement from the package was to work only with the batch facility, an argument would have existed to support the fact the entire project could have been completed in Excel or a structured language. This argument however is purely on an interface level as MS Excel was discounted as an appropriate platform due to the technical issues regarding data boundaries described at 3.8.4 *Random access file format*. The current interface for the batch facility is therefore a simple design, unlike the various forms and interface constructions within the user facility.

4.2.1 Visual Basic (VB) as a Graphical User Interface (GUI) programming solution

VB is a programming language that allows Windows applications to be developed relatively quickly. VB is both a 4th Generation Programming Language and an Event Driven Programming (EDP) Language. This means the language allows a program execution flow to be determined by events, and for the application to be built up around a GUI, such as Windows. The events within an EDP/4th Generation language are usually triggered by command buttons, drop down boxes and so on. Within this development (where the user can be presented with a large number of variables that are the results of various calculations) the use of 4th Generation Event Driven Programming environment is an ideal solution.

There are disadvantages to EDP, mainly in terms of the logic within the methods. It is difficult to control the program flow, unlike a structured programming method where you always know which line of code is executed next. This may sound a little obvious as it is an EDP language, however, when there are many methods and many events, the combination of where any particular line of code can be triggered from the variety of differing events can be problematic. Testing is therefore more difficult with EDP than structured methods as the combination of events has to be looked at very carefully to ensure the data (external variable of input/output file) is accessed at the desired time.

4.2.2 Event driven and structured programming methods

Although the interface of the project is a classic EDP development, there is still a significant proportion of the program design in a structured programming format, which is programming technique usually referred to as a 3rd generation programming. It has already been shown how the batch method could have stayed within the Excel

platform as it is essentially a structured program that does not need any user interaction, other than a single command to execute the batch operation. The input files are in place for the various methods to work in sequence until a result is gained. The user facility on the other hand uses the same data but does require various user interactions (events) to gain a result.

4.3 Batch operation and outputs

The batch operation of the program uses structured programming format which is a 3rd generation programming language technique. This means is the code is executed in a linear fashion working from start to finish triggered by one command to run.

The batch method in essence is a collection of small program methods that carry out specific and usually individual tasks. It is triggered by an event placed on a window command button and the 16 main methods (required to produce the final profit/loss results) are run in sequence one after the other. Once the button is activated the first line command is to call the first required method and therefore the flow drops into the called method. Once the flow has reached the end of this method the code returns to the button event method and the next line is executed which is another method call and so on.

There is also an added feature where the user can use interface buttons to call any of the specific methods in the batch process. As well as being a usable function this was also used in the development of the project as means to test and save time while testing. For example, if there was a problem within the 10th method in the batch process, then a modification could be made at this stage and the remaining methods could be run from the 10th method onwards providing valid data exists from previous methods. Otherwise, the whole sequence would have to be run from the start which takes around 20 minutes in total for an average specification personal computer. *Figure 3.11* shows a simplified flow of the batch process, detailing the method interactions with each other, and the various datasets produced as output then used later as input. The reference number in the flow chart processes in *Figure 3.11* is an index, and details the order of the 16 main methods. *Figure 4.18 Run individual batch processes screen* shows the 16 methods ordered from the top left to bottom right.

The batch operation itself runs through a logical process where the results gained at each method stage are used in the next method stage. The first stage is to check each device that is stored within the database to see if it matches the criteria of each site on water depth, distance from land, and resource. These values are assumed by the model to be the three main physical constraints for each device, and if they do not match the criteria then no further tests will be carried out for that device. The logic checks that each device passes all three criteria in order to be used in further analysis by the model.

The way in which the model does this is to look at each device within the database and with each device, each single site value is compared to the controlling factor, e.g. device maximum water depth with DTI water depth. Once each site has been checked then the next device within the database is selected and process is therefore repeated until the end of the device dataset has been reached. The output from this section is a file for each device. Sectioned within this file for each site is a value showing whether the device has passed or failed the criteria set. A union process is then run to amalgamate the three physical properties to find out which devices have passed all three. This result is a “true” or “false” indicator at each site where the device can be placed with regard to the three physical restrictions. There are obviously many other physical constraints that would be in place as described in the original design.

Once a union file is produced, the batch method continues through various methods that produce a random access file at each stage. The overall output from the batch method is again a random access file in the usual form of a matrix showing an indication at each site of a profit/loss value where valid. A separate profit/loss file will exist for each valid device with each cable type. The methods required to do this, their interactions with other methods, file and database input/output are explained fully in *Appendix A batch algorithms and calculations the model uses*.

The batch operation also uses various methods to enable testing, data querying, statistical analysis and display of the results produced by the model. The design and operation of these methods is fully described in *Appendix E, algorithms and calculations used for display results facility* and *Appendix D algorithms and calculations required for random access test facility*. Therefore, there are a range of outputs from the batch operation: random access files, database record sets, and, on

screen loaded data. The outputs of the batch operation can also be seen in the form of screen shots in: *4.5.2 Batch operation example walk through*.

4.4 User operation and outputs

The user operation on the other hand uses only on screen facilities to display its results. To do this the user operation uses standard Windows GUI techniques in an event driven mode. The methods behind this carry out various calculations that are described in *Appendix B algorithms and calculations required for model user operation*. The outputs of the user operation can also be seen in the form of screen shots in: *4.5.1 User operation example walk through*.

The outputs from the user operation are displayed over 9 forms, with various Windows GUI display functions. These follow the Windows convention that strictly stipulates the Windows objects that should be used to display and manage particular data and events. In brief, data that is not to be changed by the user is entered in labels. Text boxes on the other hand are used for user entry or data editing. Combo (combination) boxes are used when the logic requires the user to enter a value from a data list that is already known. The data are loaded as a choice within the combo box, which also assists the user as the selection will always be correct in a validation sense.

Check boxes are used when the user is allowed to select more than one choice, while radio buttons are used when the logic wishes the user to select only one option from several. This convention also applies to the entire application and not just the user operation, although the majority of Windows objects are contained within the user operation. This brief introduction to the Window programming convention is essentially good practice Human Computer Interaction (HCI) techniques, that are strictly followed within the application.

4.5 The function of the application model

The operation of the application is complex and is best understood through its use. Since this is not possible within the structure of this thesis, the operation of the model will be described with specific examples that will explain the methodology. It may be beneficial for the reader to load up the application and follow the documented

sequences. For information on installing and running the application please refer to *Appendix K Guide to accompanying electronic material*.

4.5.1 User operation example walk through

When the application is launched, a progress screen is loaded while the application loads various datasets that are required before the application can be used. Once the application is fully loaded, the user is presented with a screen to enter a location.



Figure 4.1 showing the initial progress bar and Enter location of deployment site screen which is displayed when the application data are fully loaded. For the batch menu the user does not need to select a location as this is only relevant for the user operation. A proceeding menu could have been used for Batch and User, however this would have created an unnecessary level and screen at this stage.

The screen is loaded with combo boxes to allow the user to select a latitude and longitude of a site. The combo boxes are set so that the user cannot select a site that is outwith the bounds of 61.5° north to 54° north / 9.75° west to 3.375° east. The screen print above shows the available choices for latitude degrees. If for example 61° is selected then the minutes is automatically set to be within bounds, and the minute combo box is updated to only allow from 0 to 29. This theme of logic controls all the combo boxes to ensure a valid choice is selected within the project boundary. After selecting a location (which will be the centre of the nearest data cell from the user selection) the user can continue with the user operation by selecting the “Enter Location” button. The batch menu button on the other hand will take the user to the batch operation and is described in *4.5.2 Batch operation example walk through*. On this occasion it is assumed the user has proceeded with the user operation and the following form is loaded.

Site Details

Characteristics of Site

59° 59' 0" -3° -3' 0" Data row 91 Data column 262

Water Depth (GEBCO)	-84 Metres	Water Depth (DTI)	-86 Metres	Distance to Closest Shore	37.8 Nautical Miles 69.7 Kilometres
Closest Power Station Point to Point	EMEC (Tidal Power Landing Point)		50.4 Nautical Miles 93.3 Kilometres	<input type="button" value="Show Station"/>	
Closest Port Point to Point	Moclett (Papa Westray)		38.3 Nautical Miles 71 Kilometres	<input type="button" value="Show Port"/>	
Closest Power Station from Sector File	EMEC (Tidal Power Landing Point)		50.8 Nautical Miles 94.1 Kilometres		
Closest Port from Sector File	Moclett (Papa Westray)		38.8 Nautical Miles 71.9 Kilometres		

Wave Properties				Tidal Properties			
Annual Mean Hs	2.85 Metres	Summer Mean Hs	1.82 Metres	Annual Mean Power	0.03 kw/m2		
Annual Mean Tz	7.52 Seconds	Summer Mean Tz	6.25 Seconds	Mean Spring Peak Flow	0.61 ms-1		
Annual Mean Power	34.37 kw/m	Summer Mean Power	11.47 kw/m	Mean Neap Peak Flow	0.3 ms-1		
Autumn Mean Hs	3.08 Metres	Winter Mean Hs	3.56 Metres	Mean Spring Power	0.11 kw/m2		
Autumn Mean Tz	6.25 Seconds	Winter Mean Tz	7.96 Seconds	Mean Neap Power	0.01 kw/m2		
Autumn Mean Power	39.96 kw/m	Winter Mean Power	57.26 kw/m	Mean Spring Range	1.96 Metres		
Spring Mean Hs	2.67 Metres			Mean Neap Range	0.86 Metres		
Spring Mean Tz	7.26 Seconds						
Spring Mean Power	29.03 kw/m						

Device Selection Criteria

Find Devices, checked on: ☒ Water Depth (DTI) ☐ Distance from Land (KM) ☐ Resource (Annual Mean) ☐ Resource within: 10 %

Figure 4.2 Characteristics of site screen in the user operation.

This form loads the physical characteristics of the site location that the user has selected. There are various properties displayed here which are mainly self explanatory from the screen print. However some do require an explanation. During the development of the model different datasets and calculations were used at different times. The user operation of the model in many ways acted as a testing facility so some datasets and alternative calculation methods have been left in to allow cross referencing, and therefore ensure the model was working to design. This is evident above with the two values for water depth, and the two values for closest port and power stations. The distances can also be cross referenced at sight against a distance to closest shore value.

For water depth, data from both DTI and GEBGO were available which is documented at section *3.7.1 Acquired external data*. These datasets are at different resolutions and it is therefore interesting to cross reference the screen result for the user's chosen location. The water depth values are expressed in negative metres. Unlike the GEBGO data (which expresses land values at positive metres) the DTI data does not include land values. On the occasion of a location being selected on land the DTI data file will return a "NA" value standing for Not Applicable as a valid data value does not exist for this site. The GEBGO data will however return the on land positive value. Again, this is a quick method to ensure two differing values from the two datasets correlate, i.e. when a GEBGO positive data value is returned then a NA result should be returned from the DTI data. In all further calculations within the model the DTI data are used. Therefore the GEBGO data in this sense is only used as a reference, and to shown the model can include various datasets at the same time.

The two alternate distances to power stations and ports are the result of two separate calculations. The results titled "Closest power station/Port point to point" takes the user entered location (in this case 59° 59' 0'' north, 3° 3' 0'' west) and calculates the direct point to point distance (by using a method that takes the two locations and calculating the distance between them taking into account spherical geometry, which is fully described in *Appendix A.17 Calculate distance between two given points*) to each power station and port within the database, and the results shown are the closest port/power station. The point to point calculations return a true value regardless of the user's selected location being on land or sea.

The alternate result for the required distances is obtained from two files (i.e. two files per port and power station) produced by the model that places a distance in the distance field (the nautical mile result, with the kilometre result being calculated at run time) and ID (cross referenced in the database to obtain the location name) in the other.

These files are structured within the model resolution and have an internal structure that allocates a data value sector at each increment from north to south and west to east. The results titled “Closest power station from sector file/closest port from sector file” in the screen print represent the distance to the closest power station with spare capacity, and closest port from the static location within the file. Incidentally the method used to calculate the distances within the file is the same used within the point to point method, just the starting values of the site is different. That is, from the file the increment static point is used as the start point (i.e. the centre point and therefore location of the data entry) where the point to point method uses the exact location (which maybe anywhere in the cell) and is not restricted by the resolution of the data. The reason the results differ is due to the fact the file location used to find the closest location result is at the data resolution available, as opposed to using the exact coordinates.

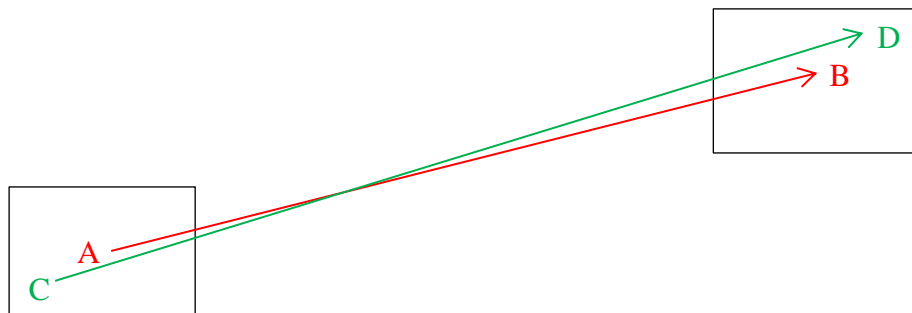


Figure 4.3 showing the difference between the two distance calculation methods. Positions C to D is the point to point method where the exact positions are measured. Positions A to B is the centre file locations dictated by the resolution of the data.

Therefore, the point to point result is more accurate as it is taking the actual point to point values of the two locations in question. The results from the point to point is shown as a reference, as the result in the file is actually used (for overall data consistency) within the model for all calculations.

The “Distance to land” value also helps show that the model is working to design as it should show in the majority of cases a correlation with the landing points, considering

the completeness of the landing point dataset, i.e. there is a substantial number of landing points saved within the database, which covers the entire geographical extent of the UK. The distance to land variable is used as various devices have a maximum limit they can be placed. For example, some offshore wave devices will have moorings to allow an element of rotation around the vertical axis (yaw) i.e. the mooring system will be set to yaw in the general direction of the prevailing swell. If this kind of device is deployed too far offshore the fetch may cause the device to rotate putting pressure on the moorings. For devices where this is not an issue, their relevant distance to land value will be set as not to restrict them within the model.

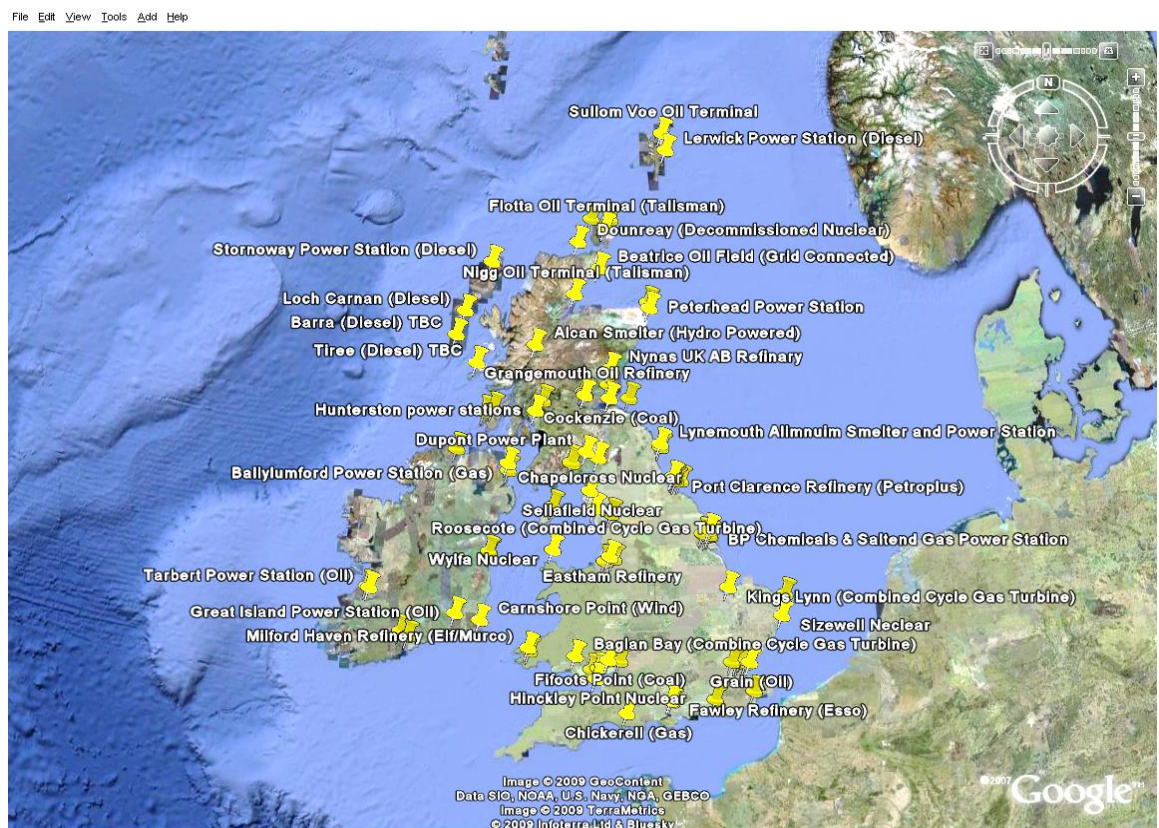


Figure 4.4 showing a plot in Google Earth of the UK, Ireland and Isle of Man coastal power station and grid landing points that are stored in the model database.

The file values are used as the model methodology works on the basis of the sector sites at the global resolution of the model (the distance files ideally have to be at same resolution as the rest of the DTI data and therefore consistent to the rest of the model). The two results shown above, show the difference from an accurate point to point method and a potential pitfall of a chosen resolution. However, it can be seen that the chosen resolution in this instance is not causing a major concern with regard to the

resulting error margin. By testing the model with regard to the study area and list of landing points and port, it can be found that the maximum error is less than 1% between the point to point method and the centre of the data file location. Since this margin is low, and that the location from within the file is the actual location being studied this is deemed acceptable. The difference in distance can actually be viewed as the difference between the user entered location, and the location of the nearest data cell (site location) defined by the model resolution, meaning the distance from the centre of this cell is appropriate to use in further calculations.

All the other data on the screen print has been sourced from the DTI other than the “data row and data column” fields which is another testing facility. These values are the location within the random access data files which directly correspond to the Latitude and Longitude of the site. In other words, this is the location system the program uses which works in an increment fashion from the north west boundary of the study area. The location of these values is beside the Latitude and Longitude of the site at the top right of the form, see *Figure 4.2*.

At the bottom of this form are three check boxes that relate to the physical criteria for selecting a device. For the model to proceed to the next screen via the “Find device” command button at least one of the check boxes has to be clicked.

The user operation of the model differs slightly from the batch operation as the user operation will allow the user to proceed to the next screen by selecting a device to pass just one or two of the physical criteria. This is to maintain flexibility where the user operation is used as a method to test the overall model and to allow a step by step operation, showing how each result has been achieved, and therefore bringing transparency to the whole process. For the model to work to the design of the batch operation then all three check boxes should be selected as these are the three physical criteria that the device must pass in order for further analysis.

The user method does not enforce a requirement that all three are selected as the user can then see (if a device did pass just one criteria for arguments sake) what the rest of the prospects for each device would be. If a user cannot understand why no devices (for example) are passing the test, then the model is allowing the criteria to be relaxed to enable the user to understand the model and how the relevant constraint operates.

The other feature that requires explanation is the combo box to control resource +/- factor. The device design resource (a method of survivability and resource extraction) is tested to be within a suitable range, considering the device's ideal resource extraction figure, which is also tested against the various power figures retrieved from the DTI datasets displayed within the "Characteristics of site" screen, see *Figure 4.2*. The way in which this is done obviously differs for wave and tidal devices.

For wave devices, the annual mean wave power figure loaded on the "Characteristics of Site" screen from the given location, is used with a percentage selected by the user in the combo box. The percentage selected is added and subtracted (to provide the given scale) to the annual mean wave power, and if the device's design resource falls within this defined maximum and minimum range then it will pass the test.

For tidal devices a similar method is used with the percentage figure being used with the mean spring peak flow to provide a maximum and minimum range in order for the device to pass

If on the other hand the user selects the "Season and cycle extremes" another scale is defined. For wave devices, the device's designed operation figure for resource is tested to fall within the winter mean wave power and the summer mean wave power, i.e. to two mean extremes during a season. For a wave device there is a clear maximum exposure due to the survivability of the device. On the other hand, the lower figure is where the device will still be able to produce electricity with the given resource. For tidal devices, the resource figure is tested to confirm whether or not it is within the mean spring peak flow, and the mean neap peak flow, the two mean extremes of the peak flow during tidal cycles.

This method within the user operation again differs slightly from the batch operation, which has a static test consisting of the season and cycle extremes method described above. A progression of the model design would be to allow the user to change the settings so that the user could define the test criteria before the overall model is run. The reason the user operation differs is to again allow a more transparent look at how the tests and data are interacting, and by changing a value (such as the percentage range) then the user can see how this has a direct bearing on the result (shown in the proceeding screen) of that specific test.

The range will allow the user to select up to 100%, which is obviously extreme and realistically there would never need to be such a positive/negative margin. However, this allows the user to see exactly how much the resource figure has to be altered (and therefore how far the resource and/or device is from ideal) for any particular device to pass this test.

The various results achieved by completing the three physical attribute check boxes and selecting a resource boundary, are described after the two information screens are illustrated (that are available from the “Site Details Screen”) for both power stations and ports.

Power Station/Landing Point Details			
Name	EMEC (Tidal Power Landing Point)		
Longitude	59 ° 9 ' 9 "	Latitude	-2 ° -48 ' -20 "
Grid Connection Zone	1 North Scotland		
Notes	5 Tidal testing berths and coastal 11kv control and switching station		
<input type="button" value="Exit"/>			

Figure 4.5 Power station/landing point details screen.

The “Power Station/Landing Point Details” form allows a little more information on the closest landing point. At present there is no more data listed for power stations and this is an aspect of the application that could be expanded. The “Grid Connection Zone” refers to the National Grid zone for connection tariff. This is not used in the working example of the model, however is an important variable if the model were to be extended to include for example the full economic analysis proposed in the initial design.

Port Details

Location: 59 ° 21 ' " -2 ° -53 ' "

Name: Moclett (Papa Westray) **Owner:** Orkney Islands Council

MHWS	Not Known/NA	Metres	MHWN	Not Known/NA	Metres	MLWN	Not Known/NA	Metres	MLWS	Not Known/NA	Metres
Tidal Date	Not Known/NA	H:M	Spring Range	Not Known/NA	Metres	Neap Range	Not Known/NA	Metres	Tidal Data Dates	Not Known/NA	

Max Berth Depth	0.5	Metres	Max DWT	Not Known/NA	
Max Berth Length	72	Metres	Max GRT	Not Known/NA	
Max Ship Draft	Not Known/NA	Metres	Fee	Not Known/NA	£/GRT
Max Ship Length	Not Known/NA	Metres	Services Code	W A	
Max Ship Beam	Not Known/NA	Metres	Pilot Restriction	NA	
Max Air Draft	Not Known/NA	Metres	Restricted Berth	Not Known/NA	ACQ/Ferry etc

Notes: 110 m pier

Exit

Figure 4.6 Port details screen.

Using the same approach as the “Power station/Landing point details”, the “Port details” form allows more information to be presented to the user. The port dataset has been set up to allow more data than actually used, with a varying number of ports at present having varying levels of data entry. None of this data (other than the actual locations and therefore distances to sites) has been used within the model methods for calculation, so it is only providing an information facility at present. This on its own is helpful to the user from a planning point of view.

The port dataset (like the power station dataset) was designed so that the various attributes could be used within various calculations and therefore refine the overall results. For example, a dataset containing ships could be directly compared to the port details to help refine an appropriate calculation on installation cost. Once this relationship is defined then the cost for this vessel at this port could be established, which would again help refine the installation cost and so on.

The nearest port is shown as Moclett on the small island of Papa Westray in Orkney. There is not a lot of data associated with this entry as it is only a small pier servicing a very small community. Other entries are more complete.

From the screen view above the only attribute that requires further explanation is the “Services code” shown to the middle right of the form. This is an entry to document the services available (as an abbreviated code) at a particular port such as fresh water, marine fuel etc. A full list would accompany the finished system to allow the user to decipher these codes. From the above example only fresh water (W) and an airport (airfield) (A) are available within the vicinity of Moclett Pier. The services code would have been used in the model coding had the attribute been used in the model calculations, which it is not. More details of how the model could be taken forward are discussed further within *Chapter 7*.

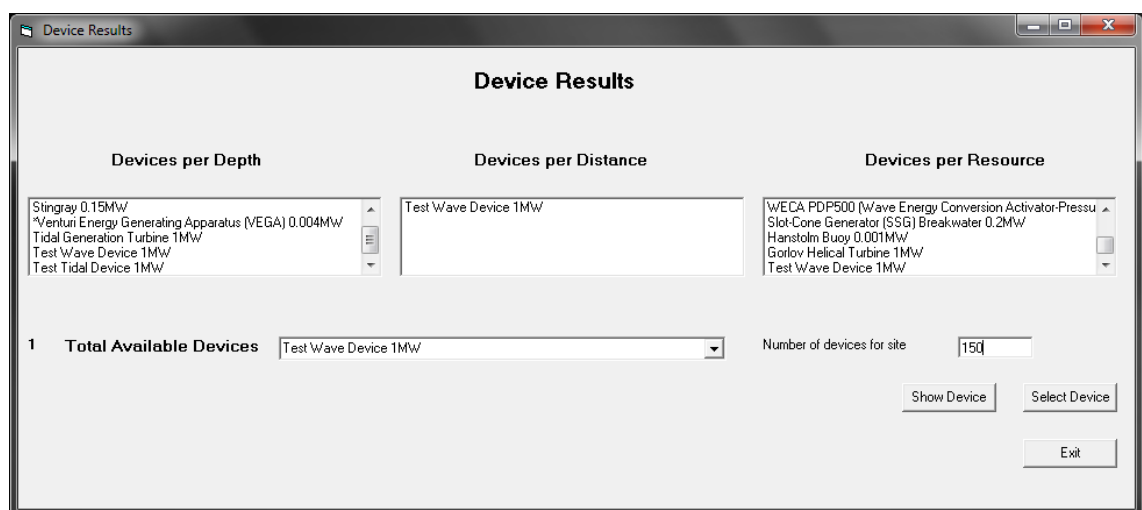


Figure 4.7 Device results screen

The screen shown in *Figure 4.7* is displayed after the “Find device” button is selected on the “Characteristics of site” screen. For this, all three physical criteria on the “Characteristics of site” must have been selected, and valid values attained at the site in order to compare, and therefore test against. This screen print is from the original location of 59° 59’ north and 3° and 3’ west with the resource combo box set at 50%.

The screen shows all the available devices specific to each criteria. If only one or two criteria were selected then only the relative criteria are displayed within the corresponding fill box area. A union of all the available devices is then worked out with

the results shown in the combo box, titled above as “1 Total available devices” The “1” in this instance shows that only one device passed all three physical tests which is a test device, that has been set up to have favourable attributes in order to test the model design. If any device does pass all three tests then these will be loaded into the corresponding result Combo box with the number of entries displayed to the left as already described.

From this illustration it can be seen that only one device (a hypothetical test device) passed all three physical criteria at this site, although several other devices passed the “Devices per depth” and the “Devices per resource” tests. This highlights the point made earlier where the user can reduce the criteria of the test, by missing out one or two of the tests, and by increasing the resource test range, in order to allow the model to continue towards a result, and therefore allow the user a greater insight to the methodology of the model when applying constraints.

To continue the user also has to enter the number of devices they would wish to deploy. The user may or may not know this number and the model actually gives the required number of devices at the next stage. However, at this point the user has to enter a number to be processed.

If a device is available then the detail of the device can then be called up using the “Show device” button. From this, the screen shown in *Figure 4.8* is displayed. An error message box is displayed if a device is not available or has not been selected.

- Mooring type, used in calculation to determine mooring cost.
- Deployment method, used in calculation to determine installation cost.
- Deployment time, used in calculation to determine installation cost.
- Design life, used in calculation to determine revenue generated.
- Tonnage, used in calculation to produce power to weight ratio, also used in the calculation of the cost of the device by taking the tonnage and unit cost of the base material(s) used to construct.
- PTO system/PTO system 2/PTO system 3, used in device cost calculation.
- Base material/Base material 2/Base material 3, used in device cost calculation.
- Base 1/2/3 %, used in device cost calculation by giving the percentage of each base material used.
- Cost of material, model generated result attribute of the cost with the relevant percentage of the base material(s) used within the structure of the device.
- PTO Cost, model generated result attribute of the cost of the PTO system(s).
- Mooring cost, mooring equipment value used in device cost calculation.
- Device cost, model generated result attribute of cost of material, PTO cost and mooring equipment cost.
- Daily installation cost, used in calculation to determine installation cost.

From the “Marine energy device” screen the “Show company” button can be selected to display the “Marine energy company details” shown in a screen print below.

Marine Energy Company Details	
Company Name	Test Company
Address	ICIT, Stromness, Orkney
Web Site	http://www.icit.hw.ac.uk
Founded	2009
Telephone Number	+44 (0)1856 850605
Fax Number	(0)1856 851349
Company Contacts	Jon Side J.C.Side@hw.ac.uk Sandy Kerr S.Kerr@hw.ac.uk Rob Harris R.E.Harris@hw.ac.uk
General email Address	E.Mackay@hw.ac.uk

Exit

Figure 4.9 Marine energy company details screen

The design and methodology behind this function is the same the “Power station/landing details” screen, the “Port details” screen and so on. Therefore this screen is used as an information facility only, and none of the details within are actually used in any of the model calculations.

Returning to the “Device results” screen in *Figure 4.7* (where the information screens for “Marine energy device details” and “Marine energy company details” lead) we can select the “Select device” button to continue.

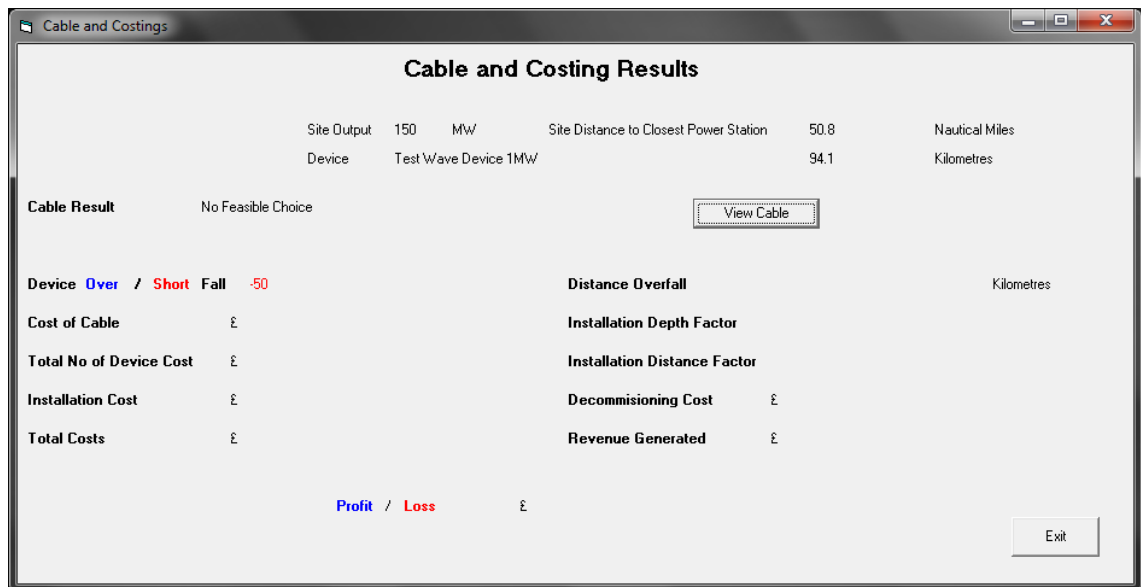


Figure 4.10 Cable and costing results screen.

The results shown above are dependent on the device chosen and the number of devices that the user has entered. As a recap, in this scenario the user selected the Test device (as it was the only device that fulfilled all the criteria) and entered a total of 150 devices. The results for a 1 MW Test device shows a 150 MW Site Output which is a shortfall of 50 devices for a feasible cable method. A minimum and maximum output range for a cable configuration has been manually set for the purpose of simulations (which is defined in the database based on examples which have been considered feasible in the offshore wind industry, and can be altered) to help determine a number of devices for a site. The cable capacities is a output range, for example the database has set 200 MW minimum and 500 MW for a 132 kV cable so any site output within this range will be valid.

Since there is no feasible cable method the calculation cannot complete, that is, it can only show the user the problem, which in this case is a shortfall of 50 devices to meet the minimum cable capacity requirement. This screen can also show the user if there is a device excess (too much output for a feasible cable choice), or a distance excess, i.e. the distance of the site is beyond a feasible cable method. In the interests of comparison the site distances are called up and are shown within the fields “Site distance to closest power station”.

Now that the user is aware that the model cannot complete the calculation due to the parameters associated with the cable, and relating parameters associated with the device array (which is determined by the device output and device number) they can now go back to the “Device results” screen (*Figure 4.7*) and re-enter a value within the “Number of devices for site”. This can allow the cable test to pass and therefore allow the model to complete the calculation. For example, if the user in this instance goes back and enters “200” in the “Number of devices” screen then the following calculation results are obtained.

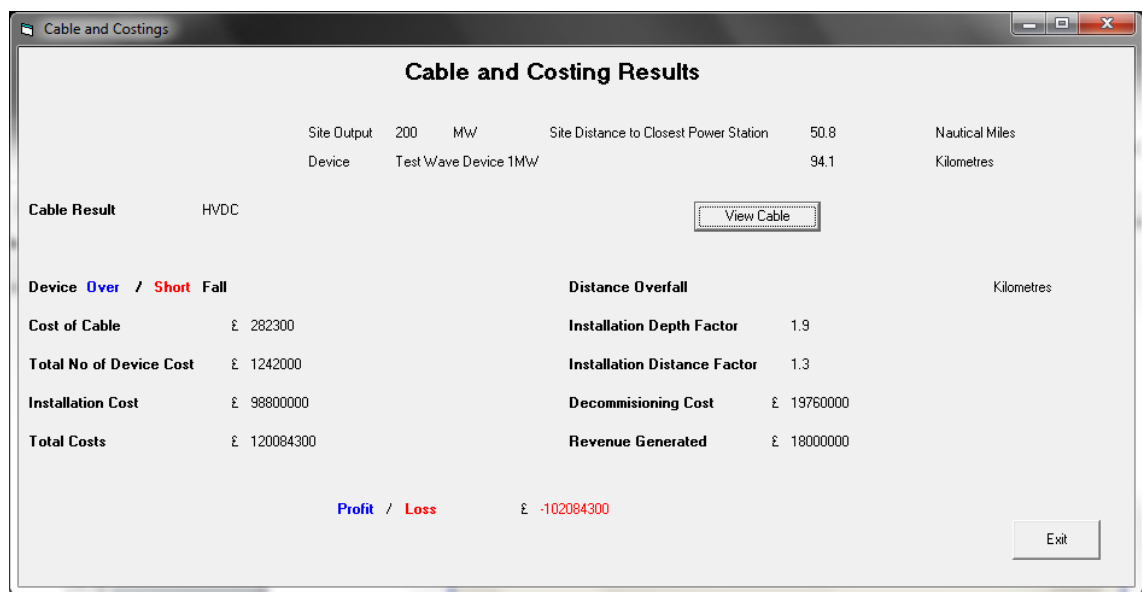


Figure 4.11 Cable and costing results screen after alteration of number of devices.

This time a feasible cable method is available (with no problems identified for device number or distance) and the associated costs of this method is shown to the user. To obtain the final profit/loss indication for the chosen site with a device, the “Cost of cable” is added to: “Total no of device cost” the “Installation cost” the “Decommissioning cost”, minus the “Revenue generated”. The “Installation depth factor” and “Installation distance factor” are values used to help obtain an “Installation” and “Decommissioning cost” by taking into consideration the depth of the site and the distance of the site to a suitable port.

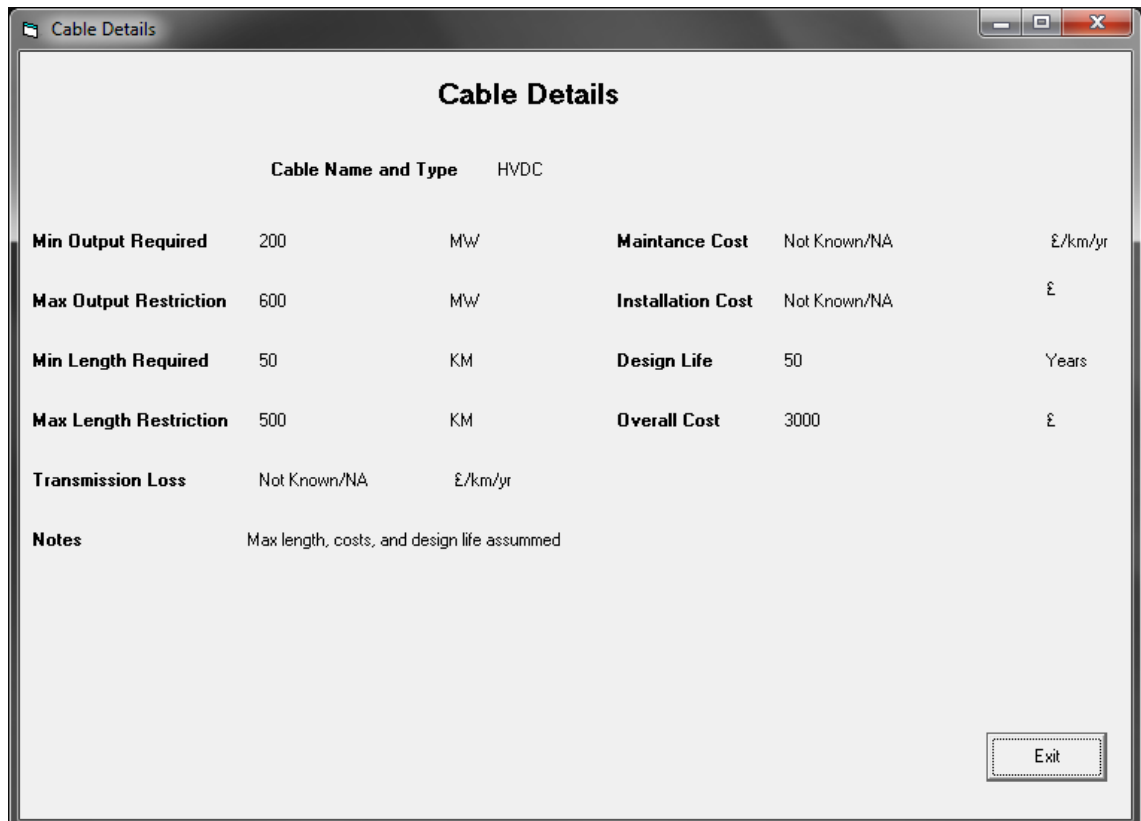
The factoring method works by a database table with a liner range of depths and distances which are scored according to the value that is assigned to this range. The resulting factor value is stored in the same table adjacent to the relevant distance/depth

which is read when the site distance/depth is found. The above example shows an “Installation depth factor” of 1.9 which relates to a depth between the ranges of >85 m and <=95 m in the database, the actual depth of the site is 86 m. The “Installation distance factor” shown as 1.3 which relates to a distance between the ranges of >30 nautical miles and <=40 nautical miles, with the actual distance being 37.8 nautical miles.

This method has been used to allow a quick scoring method to be used for depth and distance. The method also allows for the scoring values to be changed with ease within the database table. The method can be refined in the future if more accurate scoring values to populate the database were available.

The installation cost itself is produced with the number of devices, daily installation costs, number of days to deploy the device, and installation depth and distance factors. The “Decommissioning cost” is obtained by using a default percentage of the obtained installation cost.

The final progression within the user method is via the “View cable” command button which loads the following information screen.



The screenshot shows a window titled "Cable Details" with a table of cable specifications. The table has two main sections: "Cable Name and Type" and "HVDC". The first section includes "Min Output Required", "Max Output Restriction", "Min Length Required", and "Max Length Restriction". The second section includes "Maintenance Cost", "Installation Cost", "Design Life", and "Overall Cost". The "Transmission Loss" row is also present. A "Notes" section at the bottom states "Max length, costs, and design life assumed". An "Exit" button is located in the bottom right corner.

Cable Name and Type		HVDC
Min Output Required	200	MW
Max Output Restriction	600	MW
Min Length Required	50	KM
Max Length Restriction	500	KM
Transmission Loss	Not Known/NA	£/km/yr
Notes	Max length, costs, and design life assumed	

Exit

Figure 4.12 Cable details screen. Note there are some fields that do not contain data as these are not used in the working model and were to be part of the full model.

This screen is like all the other information screens within the system showing the various attributes for the entity. In this example many of the attributes are used within calculations within the model. It is important to remember that all the important attributes used in calculations are viewable to the user so the user can follow and reproduce the calculation manually so that all calculations are transparent.

The only function that is left to explain is that, forms, when loaded stay loaded so the user can compare the values on the screens without having to close and open screens. (Two relevant screens can be open side by side so the user can easily see how the model is functioning).

4.5.2 Batch operation example walk through

The batch operation of the model is activated by the same initial screen as with the user operation, which has already been illustrated in *Figure 4.1*. In this instance the “Batch Menu” command button is used to load the batch menu. The default location on the application initial screen (within the combo boxes) is not a requirement to enter the batch menu, as the coordinates are only used for the user operation of the model.

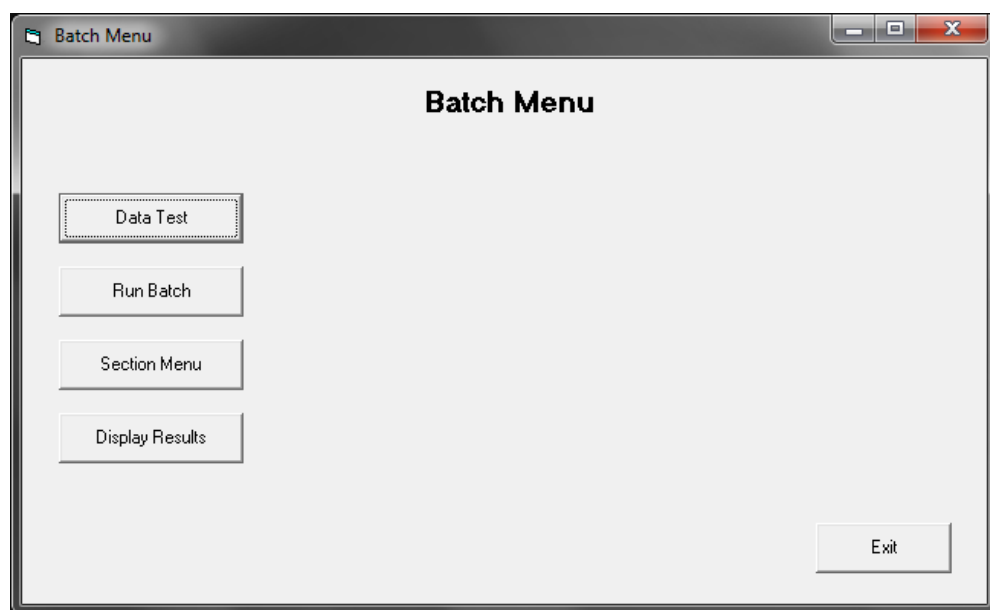


Figure 4.13 Batch menu screen

The resulting screen is the “Batch menu” from which four choices are available. For the moment we will follow the “Data test” function which loads the “Testing form” shown in *Figure 4.14*.

Testing Form

Select File Name: Data\Mean Water Depth from Tidal.txt

Selected File: Data\Mean Water Depth from Tidal.txt

Valid devices (all physical):

- 5 Pelamis 0.75MW/
- 40 Hanstolm Buoy 0.001MW/
- 70 ENERMAR 0.025MW/
- 75 Test Wave Device 1MW/
- 76 Test Tidal Device 1MW/

Data Rows: 785 Data Columns: 520

Row: 1 Column: 0 Enter

Char Size: 4 Location Lat/Long: 61.49166666666666, -9.5875 Value: NA m

Dataset Result Count NA Count: 119382 na Count: 0 Valid Count: 114618 Total: 234000

Total Profit/Loss Count NA Count: na Count: Valid Count: Total: Run Count Exit

files entries per file

Figure 4.14 testing facility screen loaded from selecting “Data Test” at 4.13. The form shows the results of position Row 1 Column 0 (start position) of the Mean water depth from tidal file. The “Char Size” indicates the number of characters in each data cell within the Random Access File, giving the total variable length.

This function was used as tool during the development of the application, but is also a valuable tool for debugging, and/or confirming the model results. The user is supplied with the complete list of all input and output files that the system uses. Any one of these can be selected from the drop down box titled “Select file name”. From here the user can select the row and column that they wish. Once the “Enter” button is selected the form loads the character size (“Char size” or variable length) of the data fields within the file, the location in latitude and longitude (“Location Lat/Long”), and the “Value” stored within this field.

The user can change the row and column value in order to test any value within the file. If the user selects a file that is specific to a device then the screen will resemble the screen shown in *Figure 4.15* below.

The screenshot shows a 'Testing Form' window with the following fields and values:

- Select File Name:** Output Files\Profit Loss Result\Device ID [Enter Device ID] HVDC max profit loss.txt
- Selected File:** Output Files\Profit Loss Result\Device ID 5 HVDC max profit loss.txt
- Valid devices (all physical):**
 - 5 Pelamis 0.75MW/
 - 40 Hanstolm Buoy 0.001MW/
 - 70 ENERMAR 0.025MW/
 - 75 Test Wave Device 1MW/
 - 76 Test Tidal Device 1MW/
- Data Rows:** 450, **Data Columns:** 520
- Row:** 170, **Column:** 182, **Enter** button
- Char Size:** 13, **Location Lat/Long:** 58.675, -5.0375, **Value:** -41914129, **£**
- Dataset Result Count:**
 - NA Count: 119466, na Count: 114532, Valid Count: 2, Total: 234000
- Total Profit/Loss Count:**
 - NA Count: 3582972, na Count: 3346368, Valid Count: 90660, Total: 7020000
- Run Count** and **Exit** buttons
- 30 files, 234000 entries per file**

Figure 4.15 Testing facility screen showing an alternative test example, this time showing a valid result that is connected to the Pelamis wave device ID 5. The Device ID has been entered into the “Select File” text box to select the file which is described below.

In *Figure 4.15* the user has selected the HVDC max profit loss file, however there will be a HVDC max profit loss file for each device that passes all three physical criteria, i.e. water depth, resource, distance to land. The devices that do pass all the criteria are listed within the “Valid devices (all physical)” list box as a reference for the user. In order for the user to test a file that directly relates to a device then the “Selected file” field has to be edited by replacing the “[Enter Device ID]” with the actual ID of one of the listed devices. In the example above the user has selected device ID ”5”, which is Pelamis. Since this was a testing tool in the development it was felt the device selection functionality was sufficient in terms of usability, however, in future revisions of the software this could be improved with another combo box containing the valid devices so the user could select one directly.

In this example the user has also made a change in the “Row” and “Column” fields to test row 170 and column 182 which has returned the value “-41914129” which is a profit/loss indication result. If the site (file location) does not contain a valid result “NA” (Not Applicable) is displayed within the field that is set up for a monetary value for valid results.

In the form, the overall statistics for the record set are displayed. This gives an indication of how many data types exist within this dataset. There are two sites within the study area which provided valid locations for the selected device. However, there were a large number of locations corresponding to land or outside the DTI data area where there are clearly no valid sites indicated by the “NA” count of 119466, and a comparable number of locations indicated by the “na” count of 114532 relating to sites which failed in one or more of the physical tests. The “NA” and “na” count values were important in the development stage of the project but could be removed for the more general use later.

In this example (as opposed to the example in *Figure 4.14*) the user has selected the “Run Count” button. This activates a function that analyses all the relevant total profit/loss files and summarizes the number of valid and not valid points at the bottom of the form. In this example there are 30 Profit/loss files with a total number of 7020000 results. However of these 3,582,972 entries were “NA” results, 3,346,368 entries were “na” values, leaving 90660 fields that contained valid data values. Once again these values were important from a development and testing point of view but somewhat unnecessary for a user once the data and model has been setup.

However, if the user or future developer were to working with new data this testing function would be a valuable tool for the user. In future revisions of the software many improvements could be made to increase the usability of these facilities for non-technical minded users.

When the run count has completed the system displays a message in order to let the user know that the calculation has completed. This is important as the calculation can take several minutes on a standard machine.

The logic on this form also validates the user’s entries so that a run time error is not encountered. This applies to the filename (a valid file name has to be entered) and the

row and column values which have to be in the range of the file selected. In order to help the user a relevant error message is displayed, also all the relevant information that is required is also displayed on the screen, such as a list of the valid devices, and the total number of rows and columns for the selected file. The “Char Size” is the size of each field within the file, i.e. character or variable length. The importance of this this related directly to the random access file format which is fully described at 3.8.4 *Random access file format.*

If we return to the batch menu (*Figure 4.13*) and select the “Run batch” command then the batch program is run from start to finish. When the program has finished its full execution, a message is displayed to inform the user the program has finished its execution run. It is important at this point to explain the “Data test” function described first within this section can only be used fully (that is with the examples above showing the various result and output files) after a full batch run has taken place. Input files can be tested before a full batch run.

The main output from the batch run is various output files. In the example below (*Figure 4.16*) the program has produced 390 files arranged in 19 folders. The data within these files totals 725 MB. The structure described here can be viewed in a Windows directory view with the “Output Files” directory showing the 19 sub directories.

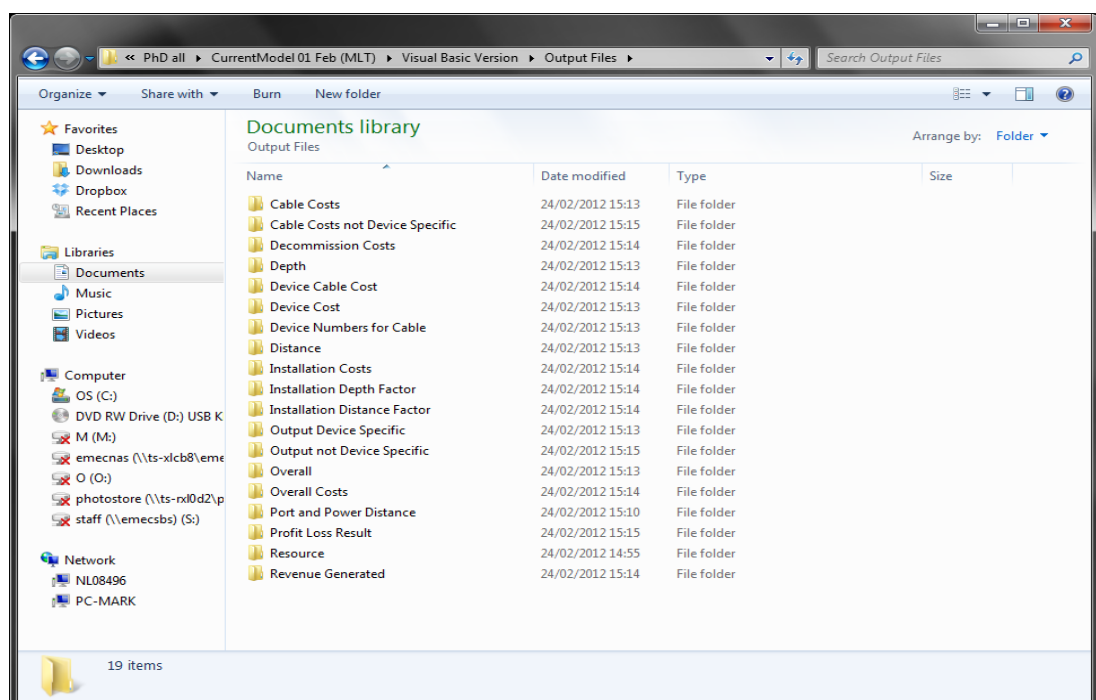


Figure 4.16 a file directory view showing the sub directory structure where the various output files are located.

Figure 4.17 below show is the directory view showing the 30 files within the “Profit loss result” folder.

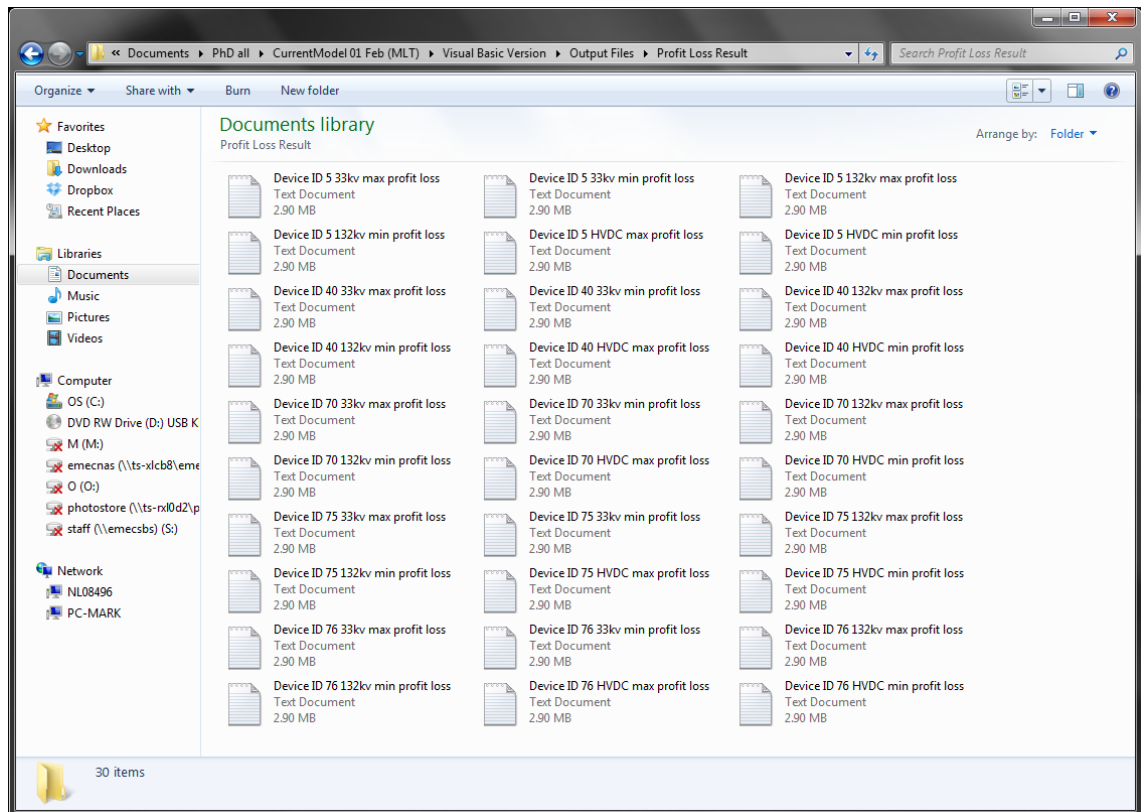


Figure 4.17 a file directory view showing the various individual output files from within the profit loss result directory. Note all files are the same size which is due to the random access format.

These files are all the same size as they all have an identical file length which is required for the random access format that was used. The files produced are for the devices that are valid, and passed the various tests along the way to an end result. The “profit loss” directory contains the final model results and therefore the devices shown above are the only devices that the model was able to obtain a result for.

These devices in this example are: device 5 Pelamis, device 40 Hanstolm Buoy, device 70 ENERMAR, device 75 Test wave device, device 76 Test tidal device. The devices

that appear in this thesis are described at *Description of relevant devices used in modelling* as well as in the Technological review within the DVD data.

For each of the devices there is the profit loss results for each cable type (33kV, 132kV, and HVDC) and the maximum and minimum device numbers associated with this cable. (Each cable type has a range in which there is a maximum and minimum MW rating, therefore this determines the number of devices at the site). The model provides the results for the maximum and minimum available devices (the device's rated power output) associated with each particular cable power rating.

These files can then be opened in applications such as Word or Notepad so the contents can be viewed. However, since the system uses an inbuilt reference system, the location is not stored in the files in order to save space. This is a slight problem in result analyses terms, however the system has a facility to view the results of the batch run in a logical fashion, which is described later in this section.

If we again take a step back to the batch menu shown in *Figure 4.13* the user can select "Section Menu" which loads the following "Run Individual Batch Processes" form shown in *Figure 4.18* which is a further menu.

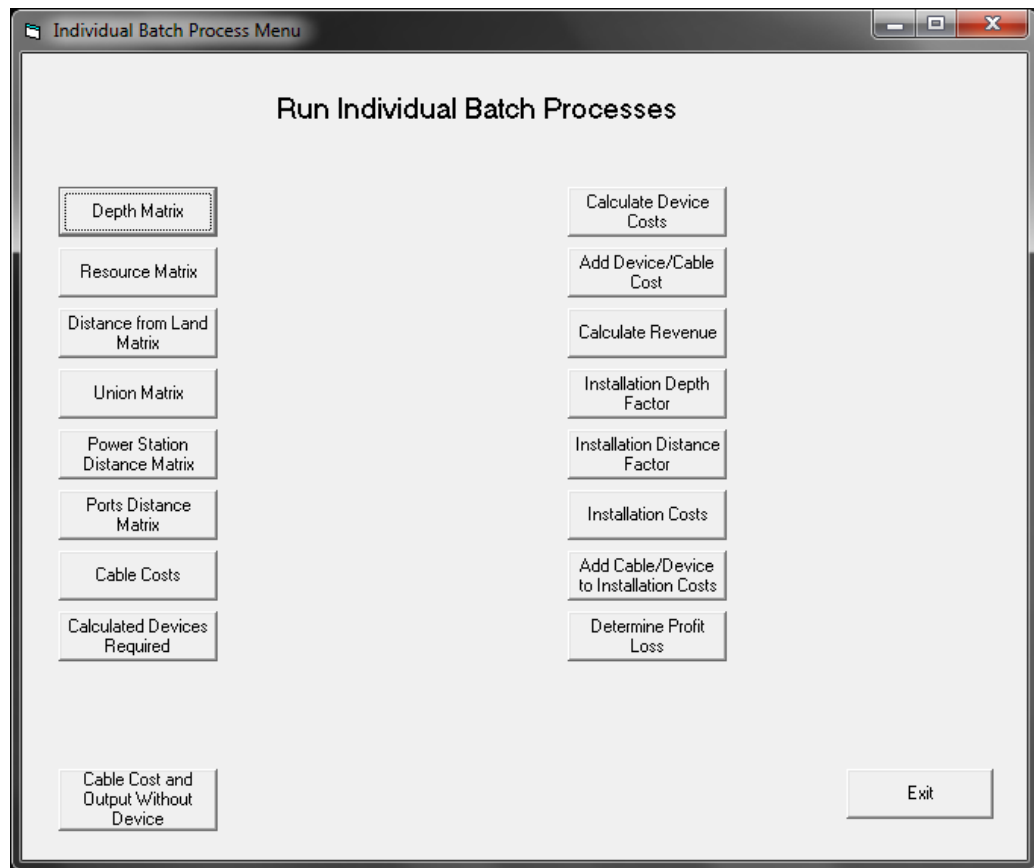


Figure 4.18 Run individual batch processes screen.

This menu shows several available options and in short these are the individual processes that make up the entire batch run. This function was used in the beginning as a function to allow testing of the batch run. If just the one section was altered then only that section of code (and subsequent methods) need to be run which saved time, as the previous results were stored and not altered in any way by progressive alterations. This is in contrast to the full batch run which will take all of the above processes and run them from start to finish. Any individual process can be run as long as the process has the relevant data for input, that is if “Cable Costs” process is run data from all the previous processes would have to exist. This is not a problem if a full batch run is undertaken before using the functions within this menu. If a change is made (say for example to a dataset) and the individual process dealing with that dataset is run again to update the results, it will only update the results for that individual process. All following processes would have to be run in turn for the results to be registered through the subsequent datasets. A further revision to the software could allow the user for example to run an individual process and all processes that follow their selection automatically.

Although this function does not serve as a useful function for an end user in the current model and data setup, it has been left in the package as the overall model is a system that has been designed to be altered and customised. Therefore this function will serve a useful purpose when the user of the model decides to make alterations or future developments. This function is also useful if (in the unlikely event that) the batch run would fail, i.e. this function can be used individually to find out where, and therefore give a clue as to why it has failed. Once a section has completed the model displays the usual “Complete” message.

The only function that is possible to run, that is not within the overall batch run, is “Cable cost & output without device” which is an historical function that was superseded by another cable cost function which is described in: *Appendix A.7 Calculate cable costs for each site against valid location for each device*. The original method is described in: *Appendix A.23 Calculate cable cost without device validation*.

Going back to the batch menu once again (*Figure 4.13*) if we select the “Display results” command button we have a facility to view the results of the various output files.

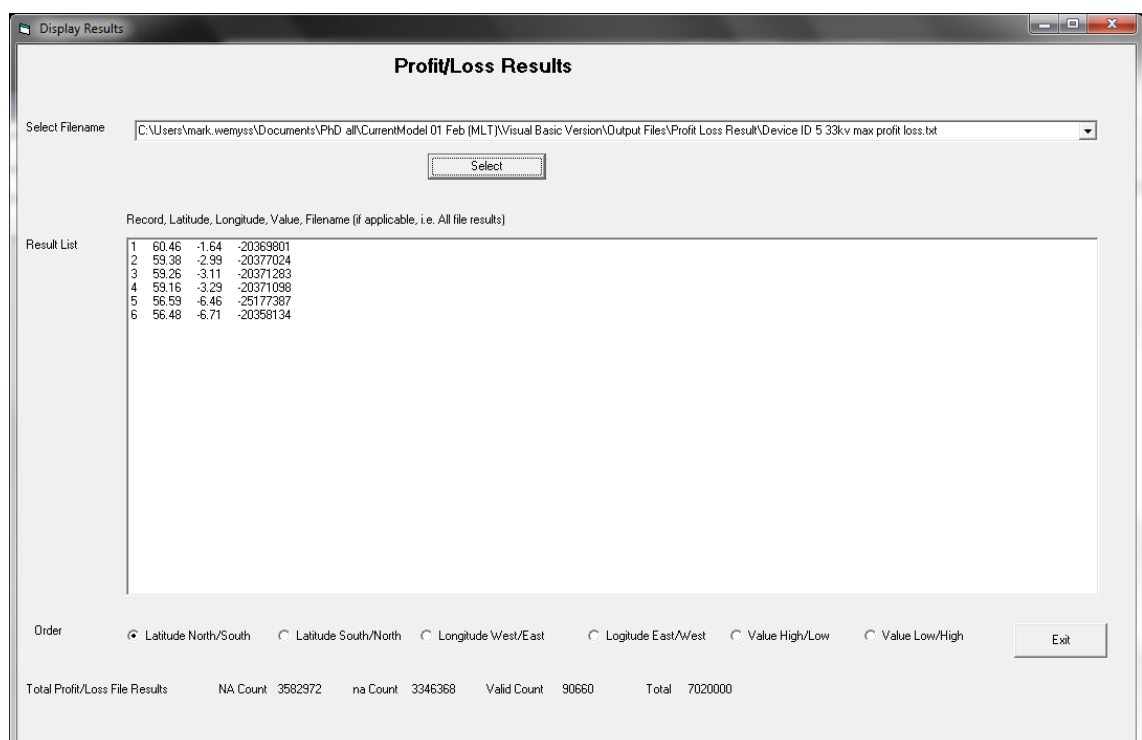


Figure 4.19 Profit/loss results/display screen.

The files that are available to view with this function are the overall resulting profit/loss files. These files are for each valid device with each cable maximum and minimum type. For each device there will be potentially 6 files, a minimum and maximum for each 33kV, 132kV, and HVDC cable. If of course no valid results for a device/cable exist, then no results can be displayed.

While any individual file may be selected within the combo box at the top of the screen, there is also an option to select “All” files in which all 90660 valid results (from our example batch run) will be displayed in the main results list area in the centre of the screen. The figure 90660 in this instance comes from the total number of valid sites found for all devices and all cables.

The way in which these results are collated is by the final function of the batch process using a condition that when a valid result is gained, then this result along with the device and cable type (i.e. the result filename) is stored to the database so the above form can use this dataset to call up the valid results. For the relevant valid results to be displayed, a filter is then used within the database table in order to extract the relevant entries that match the criteria (filename) selected by the user in the combo box.

In the example above (*Figure 4.19*) Device 5 (Pelamis wave device) 33kV max profit/loss file has been selected and within that file there is only 6 valid results. This means that there is only 6 values that contain a positive or negative number, as opposed to a “na” or “NA” value.

The results screen also allows the user to order the results either by: latitude (north first to south), latitude (south first to north), longitude (west first to east) longitude (east first to west), value (highest first to lowest), and value (lowest first to highest). The control for this in Graphical User Interface terms is called a “radio box” control which means that only one of any of the 6 clickable objects that make up the radio box group can be selected at any one time. A future revision to the software could allow for additional levels of data result sorting.

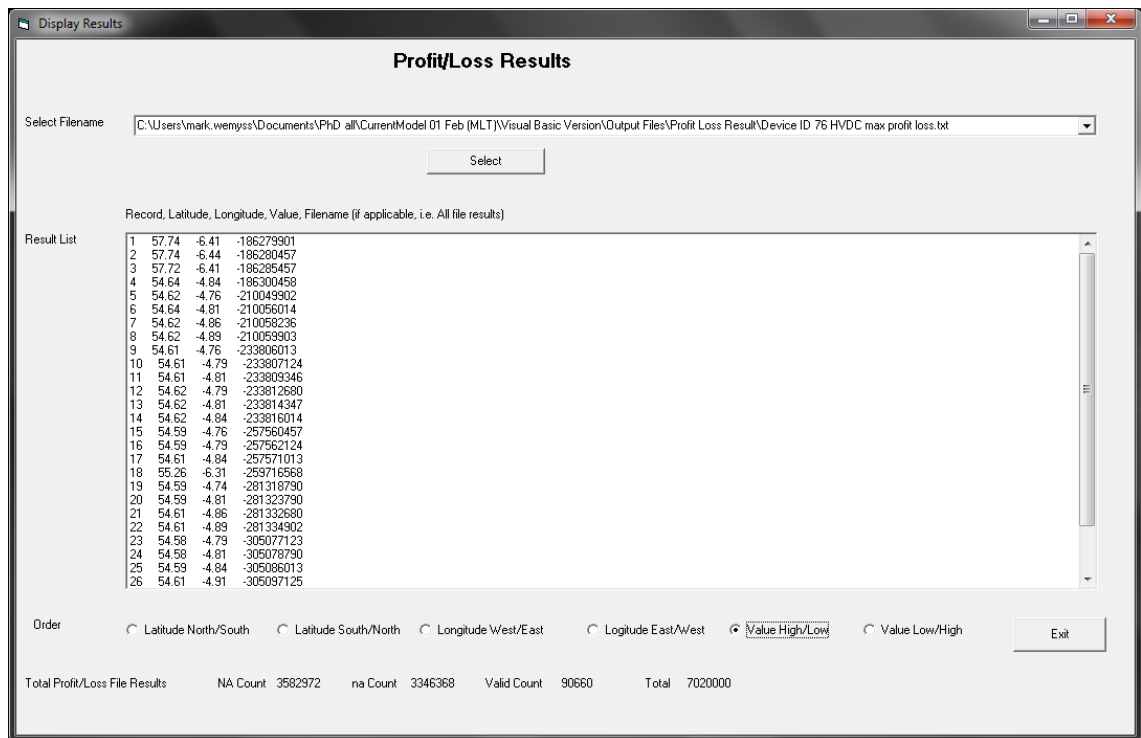


Figure 4.20 Profit/loss results screen with another example, Device 76, Test tidal device

There is also a facility to display ALL the valid results. For this to make sense the filename of each of the entries is displayed alongside the various values, otherwise it would not be known which dataset the values came from. In this example the results have been displayed from high to low.

Profit/Loss Results

Select Filename: All Select

Record, Latitude, Longitude, Value, Filename (if applicable, i.e. All file results)

Record	Latitude	Longitude	Value	Filename
1	59.31	-2.31	-8212101	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv min profit lo
2	60.69	-0.79	-8219880	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv min profit lo
3	59.84	-1.41	-8223954	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv min profit lo
4	59.82	-1.26	-8223954	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv min profit lo
5	58.26	-7.09	-10153021	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv min profit lo
6	58.56	-6.34	-12069865	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv min profit lo
7	58.66	-4.89	-14112830	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 HVDC min profit lo
8	58.68	-5.04	-14139499	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 HVDC min profit lo
9	56.48	-6.71	-16269794	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv min profit lo
10	60.46	-1.64	-16281461	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv min profit lo
11	59.16	-3.29	-16282758	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv min profit lo
12	59.26	-3.11	-16282943	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv min profit lo
13	59.38	-2.99	-16288684	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv min profit lo
14	56.59	-6.46	-20124247	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv min profit lo
15	56.48	-6.71	-20358134	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv max profit
16	60.46	-1.64	-20369801	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv max profit
17	59.16	-3.29	-20371098	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv max profit
18	59.26	-3.11	-20371283	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv max profit
19	59.38	-2.99	-20377024	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv max profit
20	59.31	-2.31	-20416101	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv max profit
21	60.69	-0.79	-20423880	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv max profit
22	59.84	-1.41	-20427954	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv max profit
23	59.82	-1.26	-20427954	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv max profit
24	56.59	-6.46	-25177387	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 33kv max profit
25	58.26	-7.09	-25237021	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv max profit
26	58.56	-6.34	-30033865	C:\Users\mark.wemyss\Documents\PhD all\CurrentModel 01 Feb (MLT)\Visual Basic Version\Output Files\Profit Loss Result\Device ID 5 132kv max profit

Order: ☐ Latitude North/South ☐ Latitude South/North ☐ Longitude West/East ☐ Longitude East/West ☒ Value High/Low ☐ Value Low/High Exit

Total Profit/Loss File Results NA Count 3582972 na Count 3346368 Valid Count 90660 Total 7020000

Figure 4.21 Profit/loss results screen with an example to show “All” valid results for all valid devices. The display shows the full path name which was required during the development, but a refinement would be to simplify the path with a filter that could be turned on or off. A full discussion of the various improvements that can be made in the future is discussed within Chapter 7.

As with the “Run count” button function within the testing function described above (Figure 4.15) there is also an overall statistical function that analyses all the total profit/loss files, and prints the various statistics associated with these.

CHAPTER 5 MODEL TESTING RESULTS

This chapter describes the white and black box testing of the model software.

As seen within section 4.5.2 *Batch operation example walk through*, the batch operation results can be viewed within a list form specifically written for this purpose. The list data are not instantly easy to understand in this format. Therefore, a graphical representation is required and this can be done with various software tools such as the various available GIS software packages, or VRML as previous described. For this thesis, the data points of interest have been plotted to Google Earth/Maps and the GIS package MapInfo.

The initial results that were plotted are the overall findings from the model with mainly known input data, with exception of 2 test devices which will be described later. That is, actual data for each existing device is known and not assumed/added for purpose of testing. Later testing then allows for values to be changed in order to see how the model reacts.

The testing regime was undertaken in five sections, or test “runs”. This is for several reasons. Weaknesses were found within the model from the initial results gained, which were corrected. Therefore the model was run again to ensure these weaknesses were eliminated. In later testing various attributes were also changed in the input database to ensure the model identified these changes, which was achieved by analysing the various distribution results and model calculations.

5.1 Structure and methodology of model result testing

The structure of the testing that was undertaken is shown below starting with a summary of the main batch test runs undertaken:

- First (initial) run, providing the first set of results from the model. Showing valid devices at valid sites.
- Second run, after the first run it was discovered that a tidal device passed a test for a site with significant wave regime, and vice versa. The logic was reprogrammed so that the opposing resource at sites were considered. This logical alteration was then successfully tested during the second run.

- Third run, after the second run it was decided to add 2 new connection points and favourably alter the data for 5 devices in order to see how the model would react. Most of the results were expected, however a data problem was found where sites positioned within certain distances from land were being ignored. The database was therefore updated to prevent this from happening.
- Fourth run, after the alteration to the database following the third run, the corrected input data were tested to ensure all valid sites were being found, which was successful. Within this test the previous alterations made (to the connection points and devices for the third run) were removed so the test acted as the second run, without the data problem previously described.
- Fifth run, for completeness the fifth run was used to test the same alterations made for the third run (addition of connection points and data alterations to the same devices) without the previously found data problem. This then allowed the distributions from the fourth and fifth runs to be analysed with confidence that the data and logic were working as predicted, which was not possible before hand for the various above mentioned reasons.

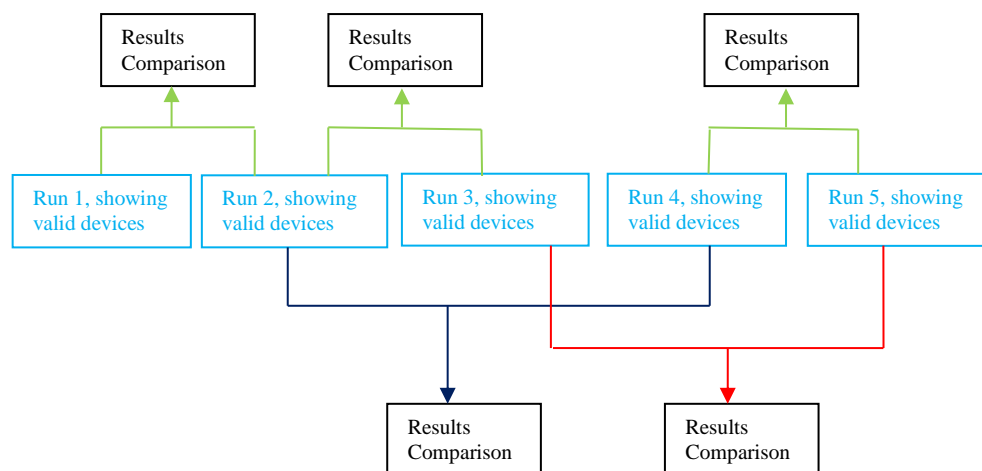


Figure 5.1 showing each model test result run undertaken with the relationship between the model runs and data comparisons. The initial first run was found to have a problem with the model logic. Run 2 therefore cures this and the results are compared to confirm this. Runs 2 and 3 are also compared to determine user level changes made to input datasets. Various valid site inconsistencies were found in the results of run 3, so run 4 and 5 were undertaken to replicate run 2 and 3 after the required modifications were undertaken to the model data. Therefore the results comparison between runs 4 and 5 directly replicated the analysis undertaken between 2 and 3. The results comparison

between runs 2 and 4, & 3 and 5 were to confirm the various required alterations to the model were successful and that the latest tests were giving acceptable results. Within each run the valid devices for a site were reviewed.

The list of devices that are found with a valid site vary through the testing. This is mainly in runs 3 and 5 where the device dataset was altered in order to see how the model reacted. The valid devices which were found are displayed in *Figure 5.2*. Runs 4 and 5 are essentially the same as runs 2 and 3 (with a data correction not linked to the device dataset). The devices found for runs 2 and 4, & 3 and 5 did not alter.

1 st run	2 nd / 4 th run	3 rd / 5 th run
Device 5 (Pelamis)	Device 5 (Pelamis)	Device 5 (Pelamis)
Device 75 (Test wave device)	Device 75 (Test wave device)	Device 7 (OSPREY)
Device 76 (Test tidal device)	Device 76 (Test tidal device)	Device 13 (Wave Star)
		Device 47 (TidE1)
		Device 56 (Hammerfest Strøm)
		Device 75 (Test wave device)
		Device 76 (Test tidal device)

Figure 5.2 showing the valid devices found at valid sites for each particular run.

5.2 Batch results from first run

The results from the first initial batch run show that only three devices made it through the various tests to the final profit/loss results. These devices were: Device 5 Pelamis wave device, Device 75 Test wave device, and Device 76 Test tidal device. The two test devices are hypothetical devices with favourable attributes used to test the model, and represent the only hypothetical data added to the device dataset at this point. A more in depth record of the above test results is documented at *H.1 Batch results, first run*.

There are a couple of important points to make from the initial batch results. *Figure H.24* shows two tidal sites off Sumburgh head which is a known area for considerable wave regime. The area in question (according to the model) has a wave regime around

32.76 kW/m. In reality, a tidal developer would avoid this site due to the high wave regime as the wave action (along with the tidal regime) will cause turbulence effects, as well as create additional structural loadings on the device that would not exist at a “clean” tidal site. This is not to say Sumburgh head will not be developed in the future, rather, it is unlikely at this stage of the industry that a site with such challenging characteristics will be commercially developed before other more manageable sites.

Therefore, this was a weakness in the model that required attention. The code was therefore altered so that the logic checks the resource for a site and device type. This works by having a default maximum wave or tidal resource figure set for each device, so that the corresponding wave or tidal resource can be validated to ensure the wave or tidal site is a clean site, without the complication of the site having a conflicting resource.

Staying in the Shetland Isles, it was a little surprising that no sites were discovered in Bluemull or Yell sounds which have a known tidal resource and also have considerable other advantages such as favourable water depth, proximity to land, and port/grid infrastructure. This can be explained by manually entering these locations to the user operation of the model where it is discovered that DTI does not recognise these areas as having a resource. This is again due to the resolution of the data combined with the shape of both Bluemull and Yell Sounds, i.e. long narrow channels, Bluemull Sound being only 0.8 km wide, and Yell sound being 2.6 km with the added complication of a 0.58 km wide island within this channel. This missed resource was confirmed when looking at the DTI atlas which is shown in *Figure 5.3*.

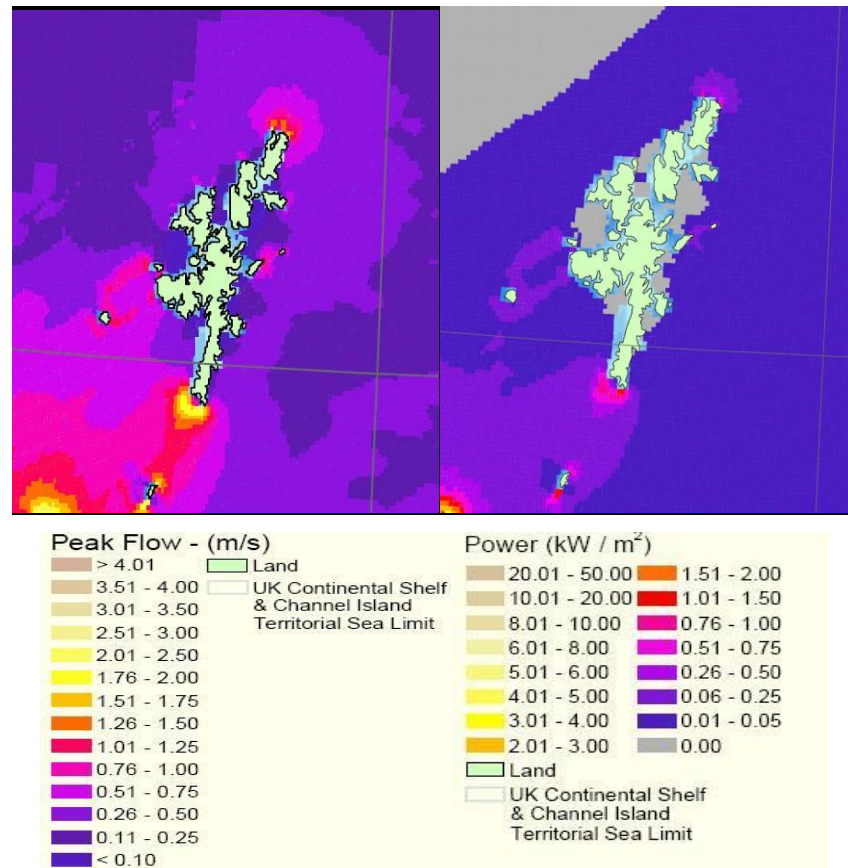


Figure 5.3 showing the DTI peak flow for a mean spring tide (left) and the annual mean tidal power density (right) with corresponding keys. The narrow inner channels to the north of the isles (which is Yell sound and Bluemull sound) show a light blue colour for the peak flow which is hard to identify on the key scale. The power density map shows the value as 0.00. Therefore, it can be confirmed from the atlas and a study of the underlying data values, the actual resource has not been identified.

This means that the data resolution within the model is not reliable around these identified areas. It is likely similar areas around the Scottish coast will have a similar weakness. This can also be confirmed from the DTI Atlas where within the data notes there is an entry: “Model accuracy is less robust in areas closer than 1 km to land”. (BERR, 2008, 2).

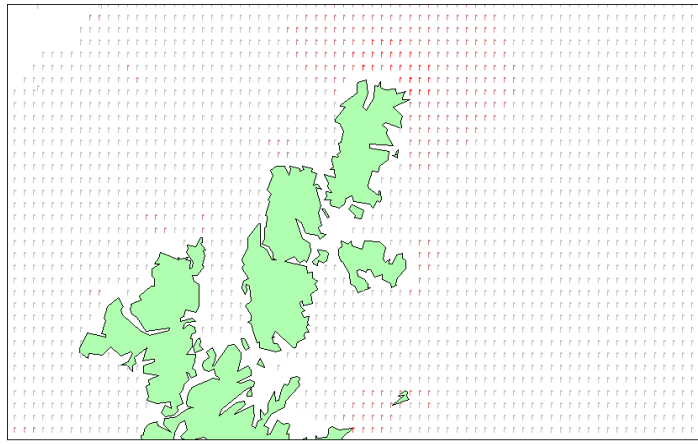


Figure 5.4 showing the tidal resource data (each point being a site with data from the DTI) which clearly shows missing data from various coastal areas and inner sounds.

The resolution weakness described above also fits with what was shown in Figure H.11 with the water depth around the northern isles of Orkney. Since all the DTI data are within the same resolution then it can be confirmed that all datasets will share the same weakness, i.e. it is not just resource data for Shetland or water depth data for Orkney that is too coarse. The data resolution used is not sufficient to adequately model inshore areas.

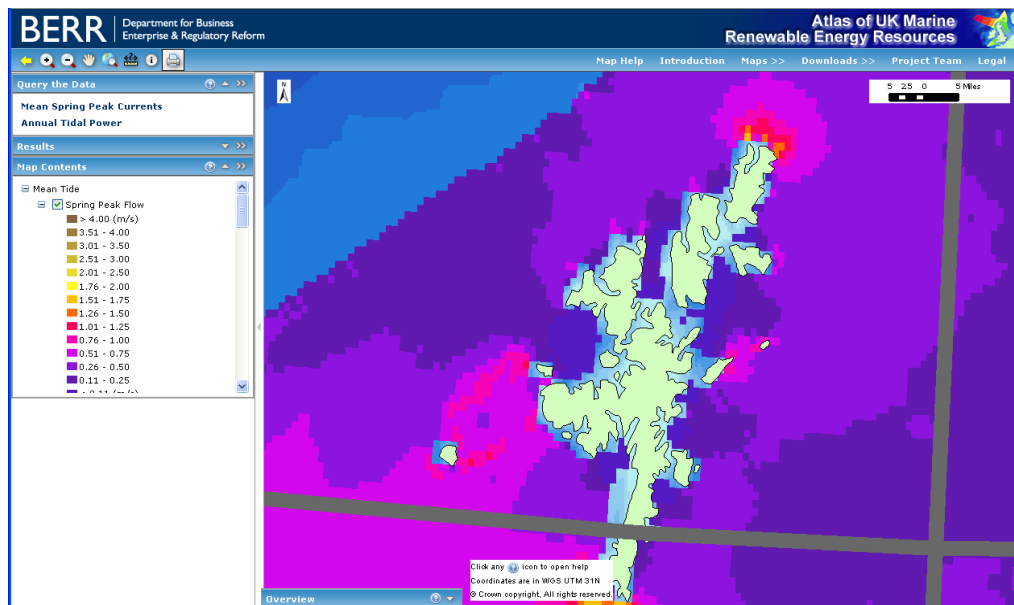


Figure 5.5 showing a later version of the DTI data which has gone through various upgrades and improvements since the initial release which is used in this research. It can be seen that the data still does not include any resource indication for the Shetland channels in question.

Following this discovery (via the Shetland Marine Energy Development Project) the Shetland Islands Council commissioned a complete resource study model for the isles undertaken by NaturalPower in 2011 (Wemyss, 2010). The initial Shetland Marine Energy Development report (and subsequent modelling by NaturalPower) therefore highlighted true resource around the isles.

5.3 Batch results after change to resource test logic (second run)

It was discovered from the initial run the results were not be acceptable in terms of conflicting resources at wave and tidal sites. Therefore, the code dealing with the resource check (with the device against the site) was changed to include an additional logical test in order to make sure a tidal site does not have a wave resource, that is in excess of the operational wave limit of the tidal device. A logical test is also included to ensure a wave site does not have a tidal resource that is in excess of the operational tidal limit of the wave device. After these changes the model has been run again, and the results show a significant change has taken place from the original batch run. To summarise the statistics, the first two batch runs are displayed below in *Figure 5.6*.

	Run 1, no of sites.	Run 2, no of sites.
Device 5 (Pelamis) 33kV	6	4
Device 5 (Pelamis) 132kV	6	2
Device 5 (Pelamis) HVDC	2	0
Device 75 (Test wave device) 33kV	4498	2661
Device 75 (Test wave device) 132kV	8177	4982
Device 75 (Test wave device) HVDC	31992	25364
Device 76 (Test tidal device) 33kV	444	1
Device 76 (Test tidal device) 132kV	175	0
Device 76 (Test tidal device) HVDC	30	0
Valid count	45330	33014

Figure 5.6 showing the difference between the first and second batch runs in terms of number of sites per device and cable. The results show the difference after the logic for the resource test was modified not to include a conflicting resource at sites.

With the latest test, the results are significantly lower for all devices. The overall valid count is down around 27%, with this figure being much higher for individual devices such as Device 76, Test tidal device.

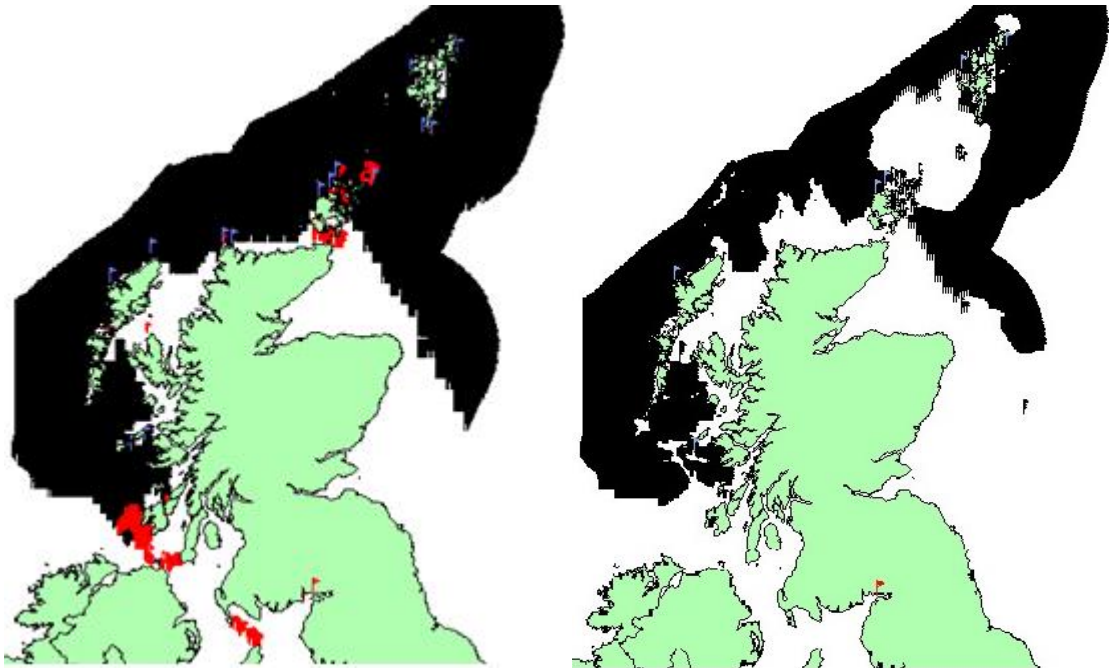


Figure 5.7 showing the distribution change for all devices before (first run) and after (second run) the alteration to the code. Device 5 plotted in blue, Device 75 in black, and Device 76 in red. Note there is only one red plot in the second run, in the Solway Firth at the very bottom of the map. All devices show a distinct reduction.

A more in depth record of the above test results is documented at *H.2 Batch results, second run*.

5.4 Batch results after changes, and additions to various database parameters (third run)

The results shown so far are for valid sites with known data before any significant alterations have been made. This is of course not considering the logical resource correction (made as a result of the first run to correct the conflicting resource) and the theoretical input test devices. The model is however designed to be flexible, so that a change to any variable (and the low level logic) can be made to see how this will alter the overall results, and therefore the distribution of sites.

For this example, several data values were changed in the database. 2 new connection points were added to the power station/landing point dataset, one in the Pentland Firth ($58^{\circ} 43' 7''$ north and $3^{\circ} 5' 19''$ west) and another in the North sea: $58^{\circ} 5' 31''$ north and $1^{\circ} 6' 27''$ west. 5 randomly selected devices were also modified to help them pass the various model tests, and therefore increase their probability of featuring in the final results. The changes are as follows:

- Wave device 7 (OSPREY) wave climate of 25 kW/m set.
- Wave device 13 (Wave Star) tonnage of 1000 tones, and 10 km from shore value set.
- Tidal device 45 (Marine Current Turbines) 5 km from shore, maximum conflicting wave regime of 5 kW/m set.
- Tidal device 47 (TidE1) 5 km from shore, tonnage of 500 tones, maximum and conflicting wave regime of 5 kW/m set.
- Tidal device 56 (Hammerfest Strøm) 5 km from shore, depth range of 30 to 60 m, and maximum conflicting wave regime of 5 kW/m set.

All the actual values for the above parameters were not known, and therefore have been added to the device dataset purely for test purposes. To summarise the statistics from the second and third batch runs see *Figure 5.8*.

	Run 2, no of sites.	Run 3, no of sites.
Device 5 (Pelamis) 33kV	4	4
Device 5 (Pelamis) 132kV	2	2
Device 5 (Pelamis) HVDC	0	0
Device 7 (OSPREY) 33kV	NA	4
Device 7 (OSPREY) 132kV	NA	2
Device 7 (OSPREY) HVDC	NA	0
Device 13 (Wave Star) 33kV	NA	115
Device 13 (Wave Star) 132kV	NA	83
Device 13 (Wave Star) HVDC	NA	55
Device 47 (Tide1) 33kV	NA	0
Device 47 (Tide1) 132kV	NA	1
Device 47 (Tide1) HVDC	NA	0
Device 56 (Hammerfest Strøm) 33kV	NA	0
Device 56 (Hammerfest Strøm) 132kV	NA	7
Device 56 (Hammerfest Strøm) HVDC	NA	0
Device 75 (Test wave device) 33kV	2661	3366
Device 75 (Test wave device) 132kV	4982	5921
Device 75 (Test wave device) HVDC	25364	23634
Device 76 (Test tidal device) 33kV	1	1
Device 76 (Test tidal device) 132kV	0	0
Device 76 (Test tidal device) HVDC	0	0
Valid count	33014	33195

Figure 5.8 showing the difference between the second and third batch run with the various planned changes.

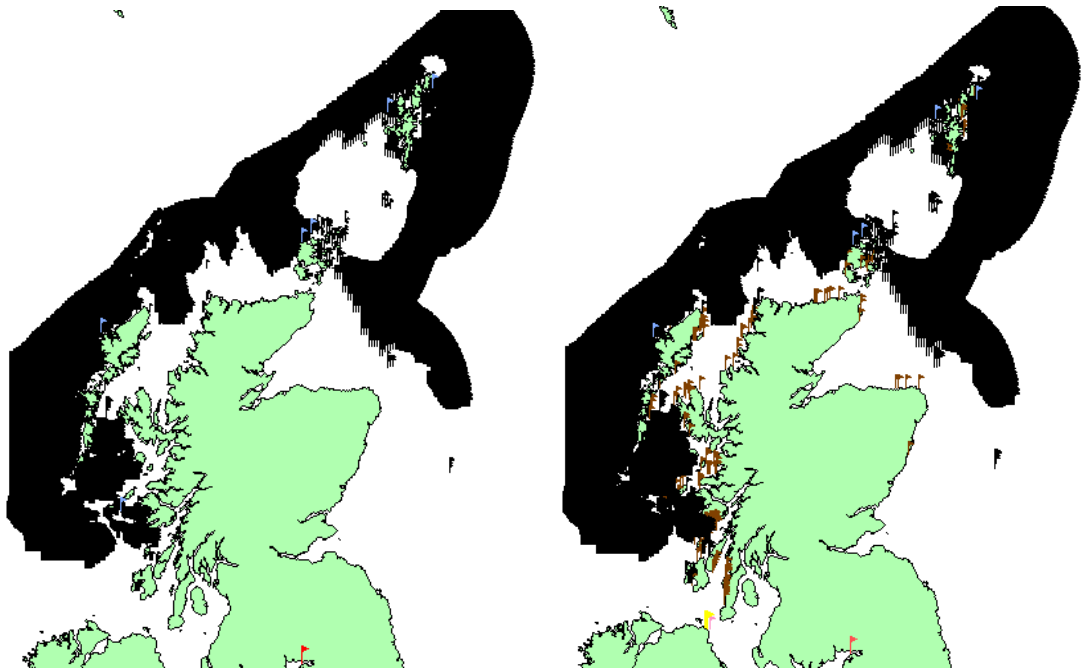


Figure 5.9 showing the distribution change for all devices before (second run) and after (third run) the alteration to various controlling data sources. Although at this scale it is difficult to notice the change in detail, it can be seen various new sites have been found, which is of course the new devices now making it to a profit/loss result. Device 5 plotted in Blue, Device 75 in Black, Device 76 in Red, Device 56 in Yellow, Device 47 in Pink, Device 7 in Grey, and Device 13 in Brown.

A script was written to examine in more detail the sites in an area 10 km² around the two new landing points using Device 75 (theoretical wave device) which returned the most valid sites in second and third runs. For the Pentland Firth landing point no new sites were identified in this area for any cable type. The reason is because these sites are in an area of high tidal energy, and the constraint of excluding wave devices in such locations incorporated in the second run excluded any such devices. For the North Sea landing point, the same 35 sites were found for Device 75 in both the second and third runs. The important difference however was the change in the profit/loss indication results which show a reduction in cost (on average 17%) and a consequential increased profit/loss value for sites adjacent to the new landing points.

This change in distribution can be explained by the fact all the sites in question can now be linked to a close connection point via a 33kV cable, as opposed to a mainland point by a HVDC cable.

During the third run a problem was found when analysing the results for Device 75. There were 95 sites found in second run that were not available in the third, and 9 new sites found in the third run that were not available in the second. These results were unexpected. On inspection it was found the logic within the model was working correctly. However, a problem was discovered with the cable dataset where a distance gap was left between the different cable types, meaning sites falling within these distances from a connection point would fail to match a valid cable, and ultimately not pass to a profit/loss result.

Therefore, the data for cables was changed to ensure there were no distance gaps between cable types that unnecessarily eliminated potentially valid sites. A full analysis of this problem with examples is documented at *H.3.7 Device 75 (Test wave device)*. A more in depth record of the entire test results is also documented at *H.3 Batch results, third run*.

5.5 Batch results after alteration to cables record set (fourth and fifth runs)

Since the previous test example runs have resulted in some form of code or data alteration being required, two further batch runs were undertaken using the previously mentioned modifications to compensate for the issues discussed above.

5.5.1 Batch results, fourth run

The fourth run was undertaken to simulate the second run, with the required alteration to the cable type dataset being the only major difference. The complete alterations for the fourth run include:

- No void gaps left between the cable types. 33kV now extended to cover up to 29.999 km (previously 0 to 29 km), 132kV extended to cover up to 49.999 km, (previously 30 to 49 km) with HVDC unchanged from 50 to 500 km.
- Removal of the two new connection points (Pentland Firth and North Sea) that were added for the previous third run.
- Device record set returned to its original state, before various devices were altered for the previous third run.

As expected, the devices that were modified in order to pass the test within the previous run, now do not show in the final results, only Devices 5, 75 and 76 reaching the final results as in the second run. There was however, a significant number of new sites found (from the second run) simply because the alteration to the cable distance attributes opened up many new areas for consideration. The summarised statistics from the second and fourth batch runs are shown in *Figure 5.10*.

	Run 2, no of sites.	Run 4, no of sites.
Device 5 (Pelamis) 33kV	4	4
Device 5 (Pelamis) 132kV	2	2
Device 5 (Pelamis) HVDC	0	0
Device 75 (Test wave device) 33kV	2661	2874
Device 75 (Test wave device) 132kV	4982	5264
Device 75 (Test wave device) HVDC	25364	25364
Device 76 (Test tidal device) 33kV	1	1
Device 76 (Test tidal device) 132kV	0	0
Device 76 (Test tidal device) HVDC	0	0
Valid count	33014	33509

Figure 5.10 showing the relationship between the data in the second and fourth run.

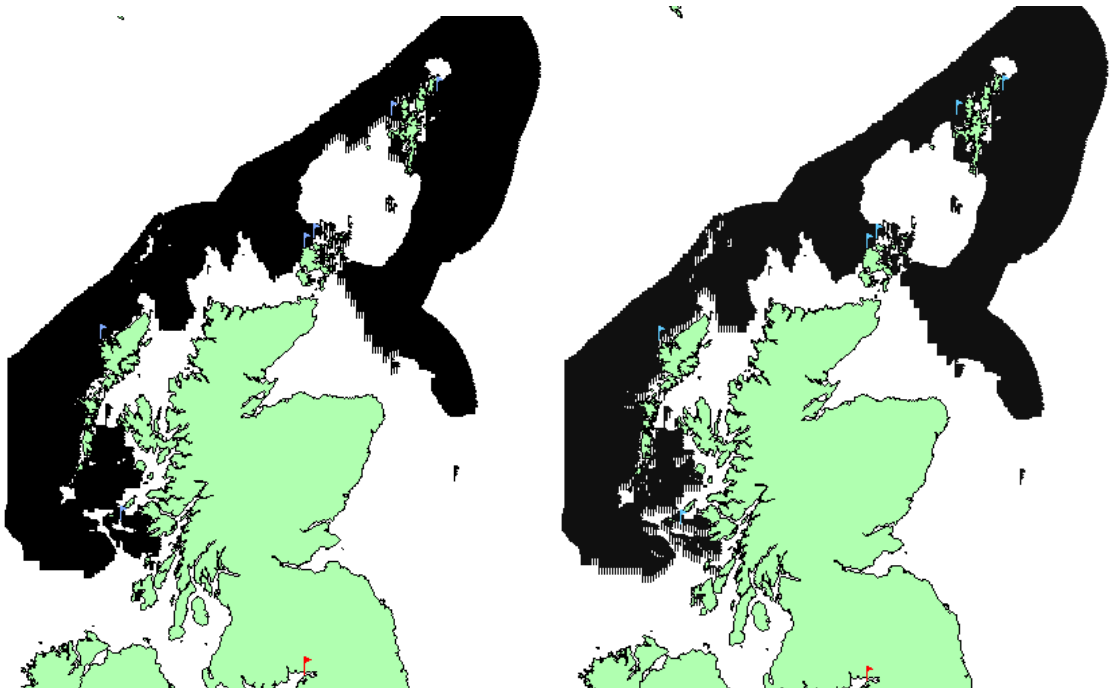


Figure 5.11 showing the distribution change for all devices before (second run) and after (fourth run) the alteration to various controlling data sources. At this scale it is extremely difficult to identify any difference in the two sets. Device 5 plotted in Blue, Device 75 in Black, Device 76 in Red.

As predicted in the fourth run, the valid site numbers increased. Device 75 witnessed the greatest increase with the 33kV and 132kV cable options both higher. The HVDC option for the same device did not increase which is expected as the boundaries of the cable distance within the database had changed for 33kV and 132kV, while the boundary for the HVDC cable stayed the same. Therefore, more 33kV and 132kV sites were found with the alteration, and the HVDC sites have been unaffected. As for the other devices there were not enough valid sites in the first place in order for the alteration to make any difference, i.e. the parameters of these devices were as such that very few sites were found in the first place, and the alteration (which has only affected sites further out to sea) did not allowed any more sites to be found.

Further data analysis was used on the most favourable device, Device 75 Test wave device. A union comparison on the data from both runs show that 33007 sites were found within the second and fourth run which is expected as this is the total of all the cable types of Device 75 in the second run. The fourth run was expected to explicitly find new sites and not eliminate already found sites from the second run analysis. This was confirmed further when no sites were found in a data difference test between the second and fourth runs, i.e. there were no data entries within the second run that did not appear in the fourth run. However (and as expected) 495 sites were found in the fourth run that were not in the second run which is a direct result of the cable attribute data change. Therefore, this change to the model has been proven to be successful and eliminates the previous weakness.

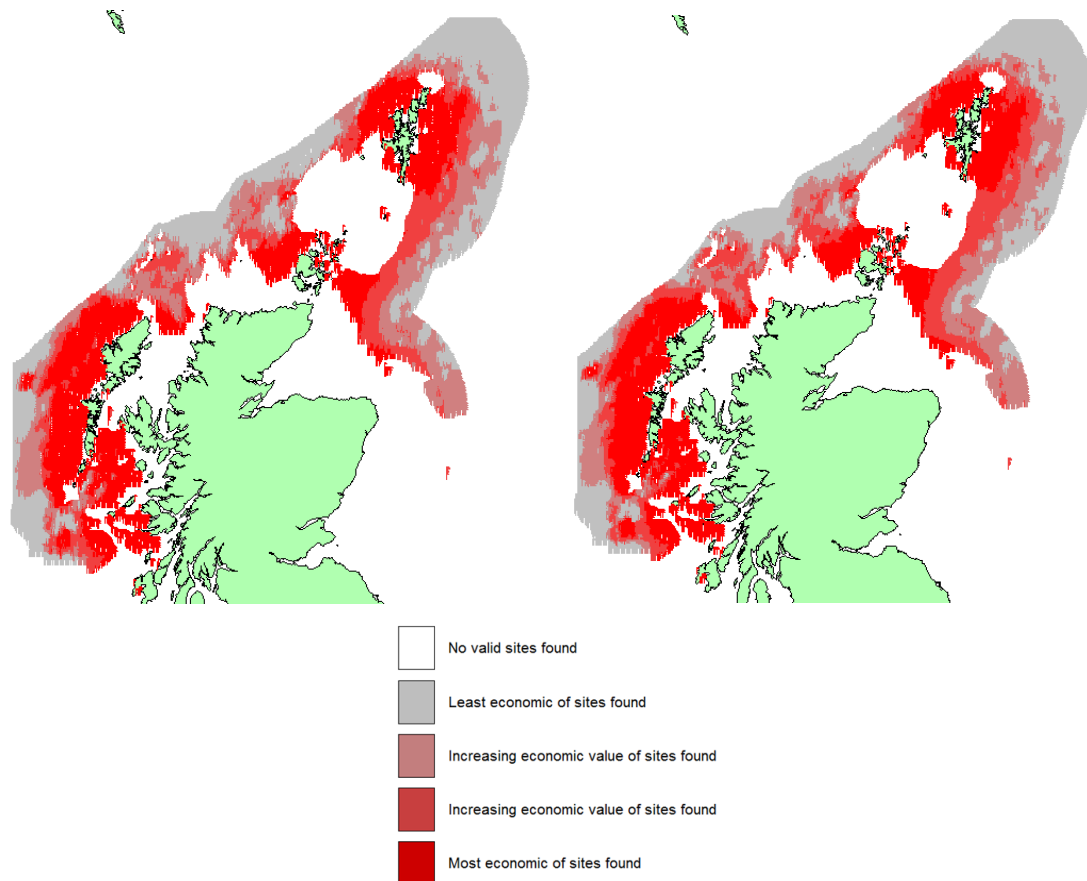


Figure 5.12 showing an overall distribution of Device 75 for the second (left) and fourth runs. The colour scheme follow the logics that the more intense the colour (red) the more cost effective the site, i.e. higher the profit/loss result. At this resolution it is very difficult to identify the difference in device numbers.

Since it is difficult to identify new sites from an overall spatial plan the 495 new sites (i.e. sites that appear in the fourth run and do not appear in the second run) were plotted in MapInfo.

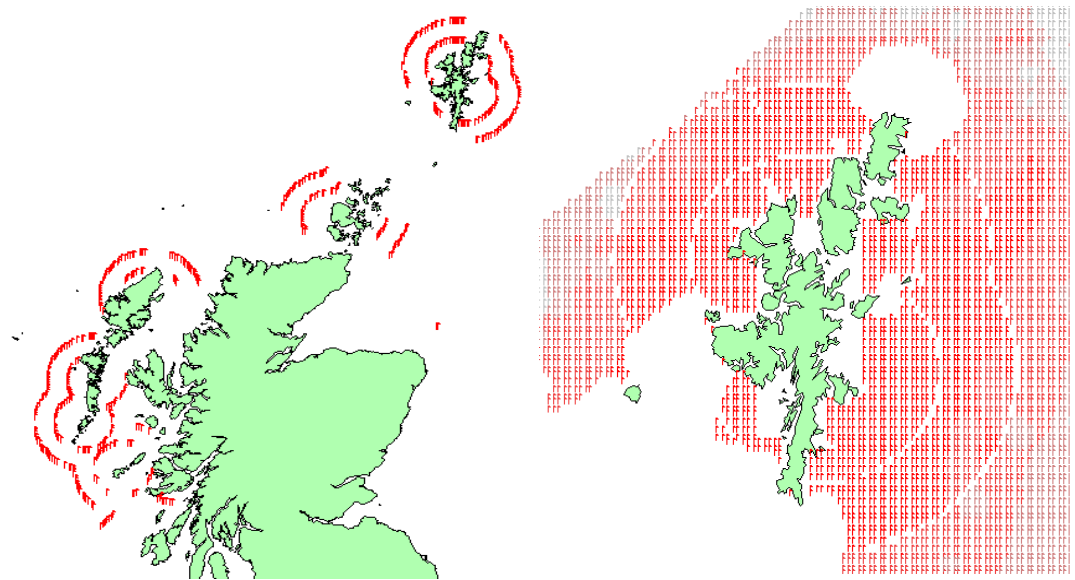


Figure 5.13 the left image shows the data difference between the second and fourth runs for Device 75. Each point indicates an individual site. 495 sites were identified which are all within 33kV and 132kV distance voids from various landing points. This problem was corrected in the fourth run and therefore these sites were identified as a result. To the right is an example for Shetland which has been focused to a level where valid (and void) sites can be distinguished from a valid site dataset previous to the cable data alteration.

5.5.2 Batch results, fifth run

The fifth run can be said to replicate the third, as the same data changes were made to the devices, with the additional connection points reinstated. The methodology behind the fourth and fifth runs is to recapture the second and third runs without the data problem (concerning the cable distances) and therefore gain a better representation of the valid sites. The summarised statistics from the third and fifth batch runs are shown in *Figure 5.14*.

As expected in the fifth run the majority of the devices that were modified in order to pass the test (which was also done in third run) show in the final results. There are also a significant number of new sites found (from the previous third run) simply because the alteration to the cable distance attributes opened up many new areas for consideration. This is mainly with Device 75 which is the significant device in terms of distribution due to it having a favourable attributes set.

	Run 3, no of sites.	Run 5, no of sites.
Device 5 (Pelamis) 33kV	4	4
Device 5 (Pelamis) 132kV	2	2
Device 5 (Pelamis) HVDC	0	0
Device 7 (OSPREY) 33kV	4	4
Device 7 (OSPREY) 132kV	2	2
Device 7 (OSPREY) HVDC	0	0
Device 13 (Wave Star) 33kV	115	115
Device 13 (Wave Star) 132kV	83	84
Device 13 (Wave Star) HVDC	55	55
Device 47 (Tide1) 33kV	0	0
Device 47 (Tide1) 132kV	1	1
Device 47 (Tide1) HVDC	0	0
Device 56 (Hammerfest Strøm) 33kV	0	0
Device 56 (Hammerfest Strøm) 132kV	7	7
Device 56 (Hammerfest Strøm) HVDC	0	0
Device 75 (Test wave device) 33kV	3366	3623
Device 75 (Test wave device) 132kV	5921	6245
Device 75 (Test wave device) HVDC	23634	23634
Device 76 (Test tidal device) 33kV	1	1
Device 76 (Test tidal device) 132kV	0	0
Device 76 (Test tidal device) HVDC	0	0
Valid count	33195	33777

Figure 5.14 showing the relationship between the data in the third and fifth run.

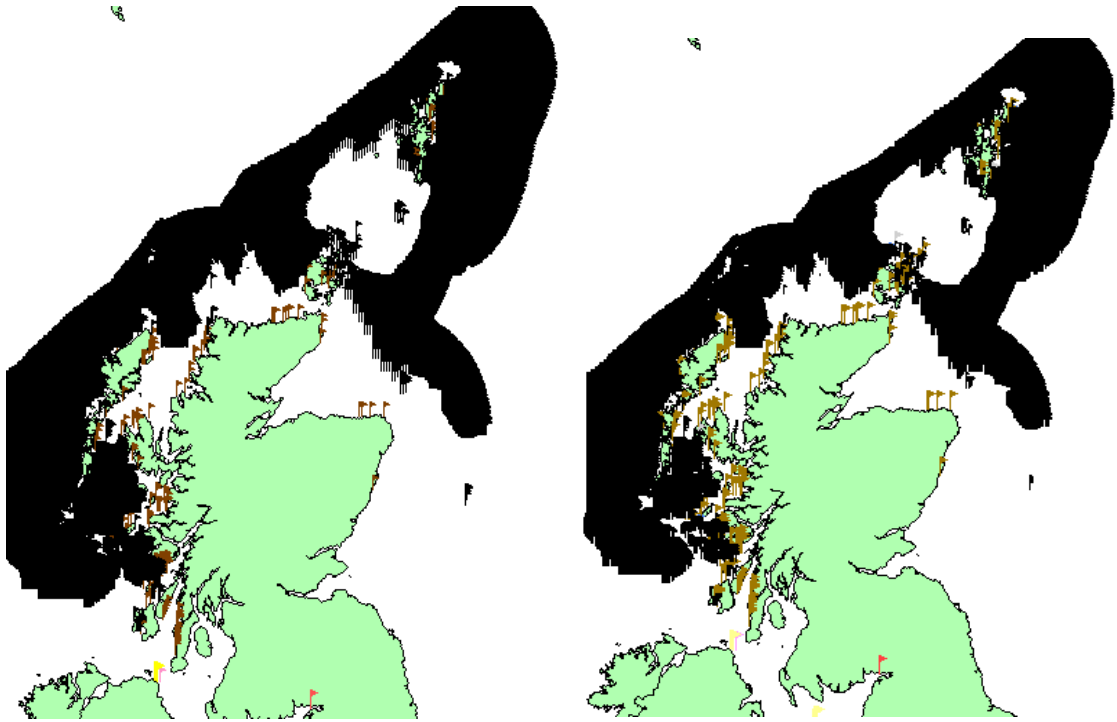


Figure 5.15 showing the distribution change for all devices before (third run) and after (fifth run) the alteration to various controlling data sources. At this scale it is very difficult to identify any difference in the two sets. Device 5 plotted in Blue, Device 75 in Black, Device 76 in Red, Device 56 in Yellow, Device 47 in Pink, Device 7 in Grey, and Device 13 in Brown.

As predicted in the fifth run, the number of valid sites increased. Device 75 again seen the greatest increase with the 33kV and 132kV cable options both higher. The HVDC option for the same device did not increase which is expected as the boundaries of the cable distance within the database were changed for 33kV and 132kV with no change to the boundary for the HVDC cable. Therefore, more 33kV and 132kV sites have been found with the alteration, and the HVDC sites have been unaffected. Device 13 (Wave Star) also had a new site identified for a 132kV cable. This was the exception to the pattern found with the other devices, as the rest of these were not returning enough valid sites in order for the alteration to make any difference, i.e. the parameters of these devices were as such, that very few sites were found in the first place and the alteration (which has only affected sites further out to sea) did not allow any more sites to be found.

The same data analysis methodology as before was again used on the most significant device, Device 75, test wave device. The union results show that 32921 sites were

found within both the third and fifth run which is expected as this is the total of all the cable types for Device 75 in run 3. (The fifth run expected to explicitly find new sites and not eliminate any sites which were found during the third run analysis). This was further confirmed when no sites were found in the data difference test between the third and fifth runs, i.e. there were no data entries within the third run that did not appear in the fifth run. However (and as expected) 581 sites were found in the fifth run that were not in the third run which is a direct result of the cable attribute data change. Therefore, the change to the model has again proved to be successful.

It is also worth noting that due to HVDC distance limit (set within the database at 500 km) there was an expectation not to find any new HVDC sites as a result of adding new connection points.

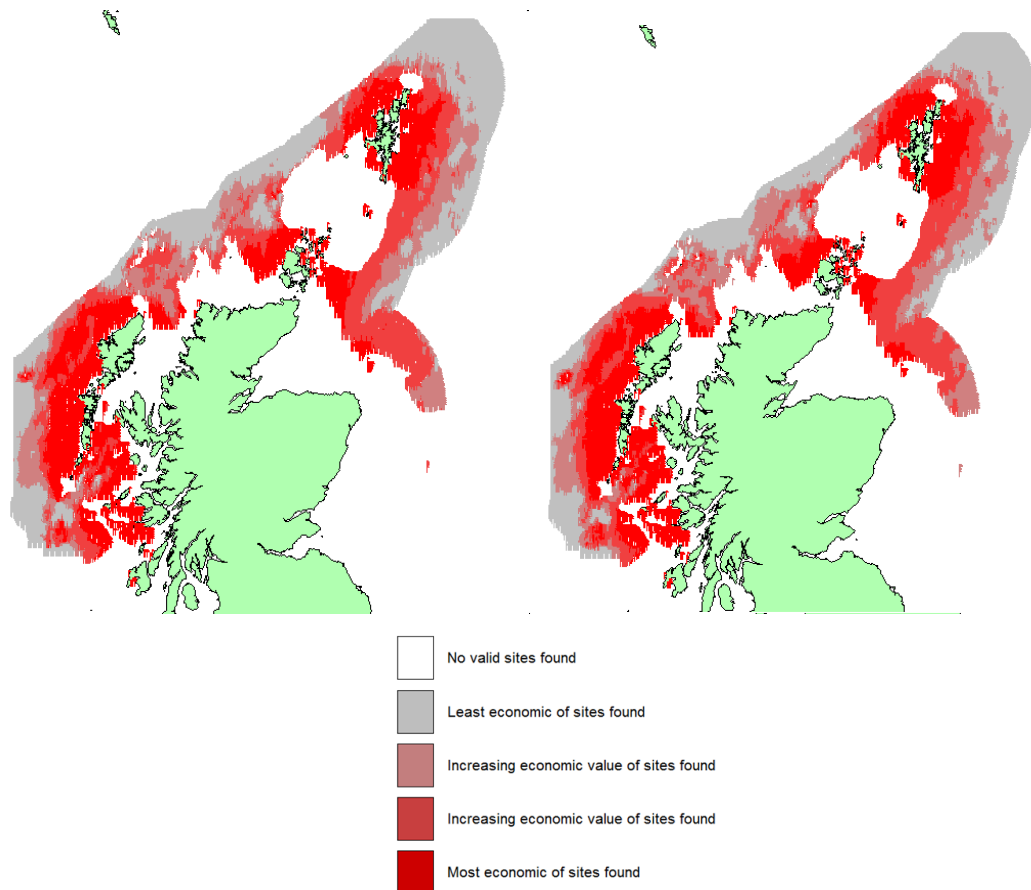


Figure 5.16 showing an overall distribution of Device 75 for the third (left) and fifth runs. At this resolution it is very difficult to identify the difference in device numbers, or the distribution change of the sites per cost.

Since it is difficult to identify new sites from an overall spatial plan, the 581 new sites (i.e. sites that appear in the fifth run and do not appear in the third) were plotted in MapInfo.

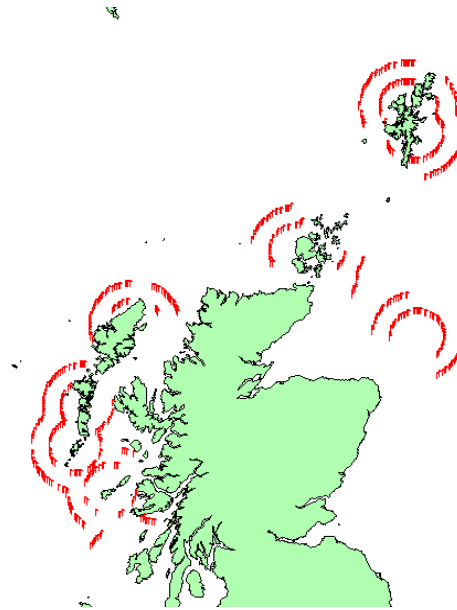


Figure 5.17 showing the data difference between the fifth and third runs for Device 75. Each point indicates an individual site. 581 sites were identified which are all within 33kV and 132kV distance voids from various landing points. This problem was corrected for the fourth run, and therefore these sites were identified as a result.

5.5.3 Batch results, comparison between fourth and fifth runs

At this point it is also worth looking at a comparison in results between the fourth and fifth runs, which are essentially the same as the second and third runs with the main difference being the alteration to the cable distance values. (The second and third runs were designed to test the change in distribution when the parameters of several devices were changed/made more favourable, and the addition of two new connection points). The methodology with the fourth and fifth runs comparison is the same, with the fourth run acting as the substitute second run (with the cable distance void plugged) and the fifth run acting as the substitute third run where the various parameters were added/altered.

Therefore, the results from the fourth and fifth runs give a more accurate picture compared to the previous second and third runs, where the cable distance issue became apparent and significant anomalies in the data results were discovered. *Figure 5.18*

summarises the results for the fourth and fifth runs for the Device 75, with *Figure 5.19* showing the spatial distribution for all devices in the fourth and fifth runs.

	Run 4, no of sites.	Run 5, no of sites.
Device 75 (Test wave device) 33kV	2874	3623
Device 75 (Test wave device) 132kV	5264	6245
Device 75 (Test wave device) HVDC	25364	23634
Total	33502	33502

Figure 5.18 showing the relationship between the data in the fourth and fifth run for device 75, Test wave device.

It is worth noting that in *Figure 5.18* only shows Device 75 as the other devices (relevant to their individual runs) were unchanged and therefore have been documented already either above or in *Appendix H*. In the fifth run there were also results from devices not found in the fourth run as a result of the various alterations made to them for the fifth run, which is not relevant for a direct comparison between the fourth and fifth runs, and were again unchanged from the third run.

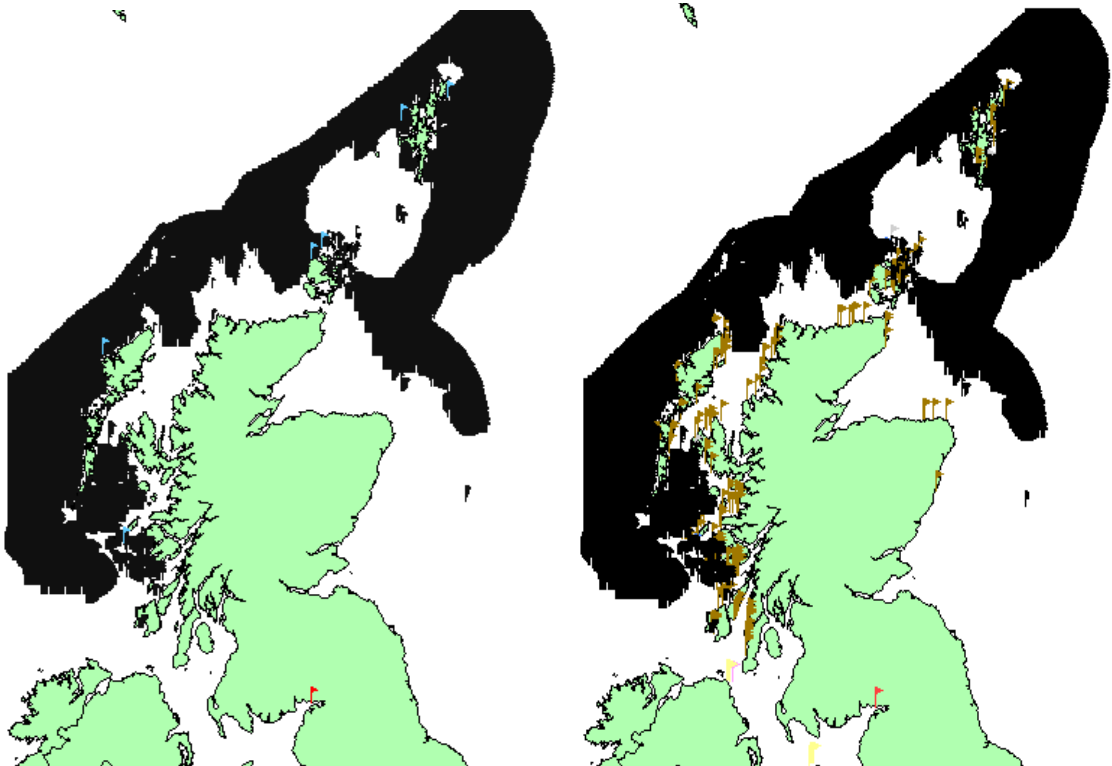


Figure 5.19 showing the distribution change for all devices before (fourth run) and after (fifth run) the alteration to various controlling data sources. At this scale it is difficult to identify the changes clearly, however the additional devices and sites can be

seen on close inspection. Device 5 plotted in Blue, Device 75 in Black, Device 76 in Red, Device 56 in Yellow, Device 47 in Pink, Device 7 in Grey, and Device 13 in Brown.

It is slightly unexpected that with the addition of the two landing points no additional sites have become available for Device 75, which has the most favourable parameters set and therefore more sensitive to changes than any other device. However, after inspection this can be explained by the fact the new connection points allowed for a change in the cable types within the area, rather than a change in actual sites which is largely down to the HVDC cable having a significant range in terms of the model boundaries.

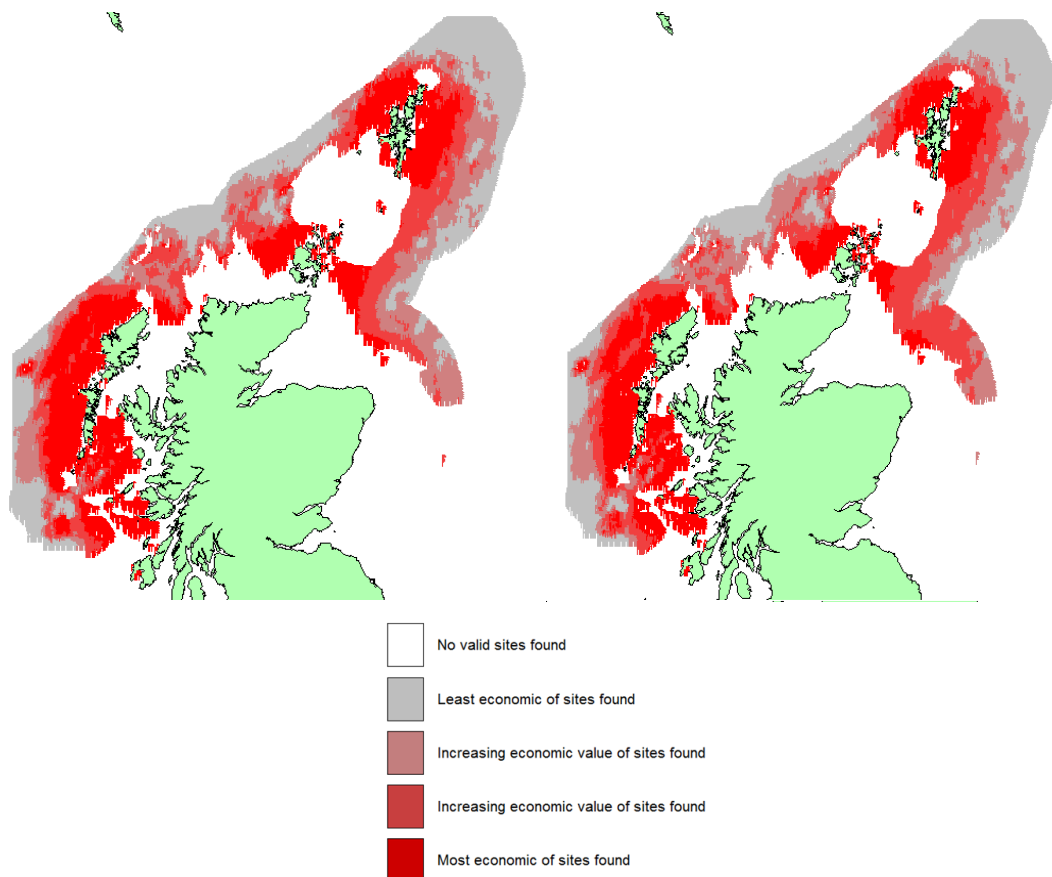


Figure 5.20 showing an overall distribution of Device 75 for the fourth (left) and fifth runs. The distribution change of the sites per cost can be identified with careful inspection. In the current analysis for Device 75 the number and location of sites were identical for both runs. The only changes appeared in the cost values in the financial model.

As with the results from the second and third runs the number of HVDC sites is lower in the fifth run than the fourth run. This is again for the same reason where the added connection points (mainly the North Sea connection point) has allowed for the valid sites within that area to be closer to a landing point and therefore use shorter cable methods. The new connection points also did not allow for any new HVDC connection due to the maximum length set for the HVDC cable (which is obviously a realistic strength of this cable type) and the fact that the database holds a comprehensive distribution of connection points meaning all sites in the study area are available from the current HVDC cable setting of 500 km.

The furthest point from land according to the DTI dataset is 301.28 km and the furthest offshore site from a connection point (fifth run) is 309.84 km. This site is located 56° 5' 2" north and 3° 15' 36" east routing to Cleveland combined heat & power plant 54° 33' 22" north and 0° 49' 18" west. Incidentally this site (furthest offshore site from a connection point) is unaffected by the additional landing points made in the fifth run.

For the study area and current list of identified landing points, a HVDC cable with its current cable length range is a valid option for even the furthest offshore site. If in the future the minimum HVDC distance value were less, then additional valid sites might have been found and this could be tested by appropriately changing the cable distance limits.

5.6 Overall summary of batch test runs

This section will provide a recap with a summary of the main batch test runs undertaken:

- First (initial) run, providing the first set of results from the model to be analysed.
- Second run, after the first run it was discovered that tidal devices passed the test for a site with significant wave regime and vice versa. The logic was altered so that the opposing resource was considered. This alteration was then successfully tested during the second run.
- Third run, after the second run it was decided to add 2 new connection points and favourably alter the data for 5 randomly selected devices in order to see how the model would react. Most of the results were expected, however a data problem was

found in that sites positioned within the distances set for each cable type were being ignored. The database was therefore updated to prevent this from happening.

- Fourth run, after the alteration to the database following the third run, the new data were tested within the fourth run to ensure all valid sites were found, which was successful. Within this test the previous alterations made (to the connection points and devices for the third run) were removed so the test acted as the second run, without the cable data problem.
- Fifth run, for completeness the fifth run was used to test the same alterations made for the third run (addition of connection points and data alterations to the same devices) without the cable data problem. This then allowed the distributions from the fourth and fifth runs to be analysed with confidence that the data and logic were working as expected.

This concludes the result documentation and testing methodology of the batch processes.

5.7 Test comparison of batch and user facilities

As stated the user and batch modes have specific purposes. The batch mode carries out the overall functional objectives of the model, while the user mode uses the same logic and data, at run time, for analysis of only one specific site at a time. Therefore, the two separate systems can actually be compared against each other to ensure they produce the same results. This is important as one of the key strengths of the user method is to allow (in essence) a testing facility for the user where they can see step by step how the model has reached any particular result within the corresponding batch operation.

Although this sounds a straightforward task, i.e. considering the two methods use the same logic and data, it still has to be tested as the actual code carrying out the logic and interpreting the data is different due to the separate operations of the methods. The batch mode takes every site (with every device) and works to a profit/loss result with no interaction with the user. The user method on the other hand takes a specific site and allows the user to select devices and conditional values and so on. Therefore, the structure of the code (albeit with the same logic) has to be organised accordingly which has resulted in separate methods for many of the user and batch operations.

Cable and Costing Results

Site Output 200 MW Site Distance to Closest Power Station 27 Nautical Miles
 Device Test Wave Device 1MW 50.004 Kilometres

Cable Result HVDC View Cable

Device Over / Short Fall **Distance Overfall** Kilometres

Cost of Cable	£ 150012	Installation Depth Factor	1
Total No of Device Cost	£ 1242000	Installation Distance Factor	1
Installation Cost	£ 40000000	Decommissioning Cost	£ 8000000
Total Costs	£ 49392012	Revenue Generated	£ 18000000

Profit / Loss £ -31392012 Exit

Figure 5.21 showing the final profit/loss result screen for the user method at site 57.96 (57° 57' 0") north -7.09 (7° 5' 0") west (or in data location terms data row 213, data column 100). To get to this point the user selected 200 (which is the minimum number of devices for the HVDC cable type at this distance from landing point) Test wave devices, which is Device 75 within the database.

Testing Form

Select File Name Output Files\Profit Loss Result\Device ID [Enter Device ID] HVDC min profit loss.txt
 Selected File Output Files\Profit Loss Result\Device ID 75 HVDC min profit loss.txt

Valid devices (all physical)
 5 Pelamis 0.75MW
 7 OSPREY 2MW
 13 Wave Star (North Sea Design) 5MW
 40 Hanstolm Buoy 0.001MW
 45 Marine Current Turbines (MCT) 1MW
 47 TidE1 1MW
 56 Hammerfest Strom (Prototype) 0.35MW

Data Rows 450 Data Columns 520
 Row 213 Column 100 Enter

Char Size 13 Location Lat/Long 57.95833333333333 -7.0875 Value -31392012 £

Dataset Result Count	NA Count 119466	na Count 90900	Valid Count 23634	Total 234000
Total Profit/Loss Count	NA Count 7165440	na Count 6807006	Valid Count 67554	Total 14040000

60 files 234000 entries per file Run Count Exit

Figure 5.22 Showing a data test enquiry for the same location (57.96° north, 7.09° west / data row 213 data column 100) for the Test wave device (Device 75) for the minimum profit/loss result for a HVDC cable, i.e. the data inputs as for the user example above.

From the test example above it can be seen that the batch operation has concluded that for site 57.96° north 7.09° west the profit/loss value is -31292012. This location within the user operation (using the same number and type of device) confirms the overall result value is the same. This confirms the separate code within the two separate methods is following the design logic, and the different modes can be used to verify each other. As a point of interest, if the overall results did not match, the data test and user method results could have been used in conjunction as above to make a comparison with each other in order to find out at what point the results differed. The testing function can call up any batch output file, with any site value displayed if required. Each stage value (i.e. each value required to eventually gain the profit/loss result) is also displayed within the user method forms so they can be directly compared if for some reason they did not directly correlate.

CHAPTER 6 – ILLUSTRATED EXAMPLE

The aim of this chapter is to show the model in use, and the true power of the dynamic approach which this research has produced.

The example has taken inspiration from various feasibility studies undertaken for the development of an east coast offshore grid. Of note are two studies undertaken for the Crown Estate: East coast transmission network, technical feasibility study by Crown Estate, Senergy Econnect and National Grid (2008), and Offshore transmission network feasibility study by National Grid (2011).

The investigation presents an indicative set of optimum offshore and onshore electricity transmission network reinforcements required for the connection of up to 46GW of generation as part of the offshore wind leasing rounds (Crown Estate, 2008 / National Grid 2011). This provides an interesting example as sections of the proposed grid upgrade can be included in runs to see how this will change the distribution of valid sites and their corresponding economic indicators.

The methodology will be similar to the previous test runs undertaken in *Chapter 5* where model runs will take place before and after the proposed east coast grid upgrade is added. For clarity, no hypothetical test devices were used for this illustration, and all landing points were set to allow additional capacity to be connected.

6.1 Data to be added to include the proposed grid upgrade

The Crown Estate propose various scenarios for the east coast network linking Shetland to north east England. The various options are not important in this context as a list of offshore coordinates were taken to represent a sample of the Crown Estate proposals. *Figure 6.1* shows the Crown Estate indicative coordinated network design for 2030.

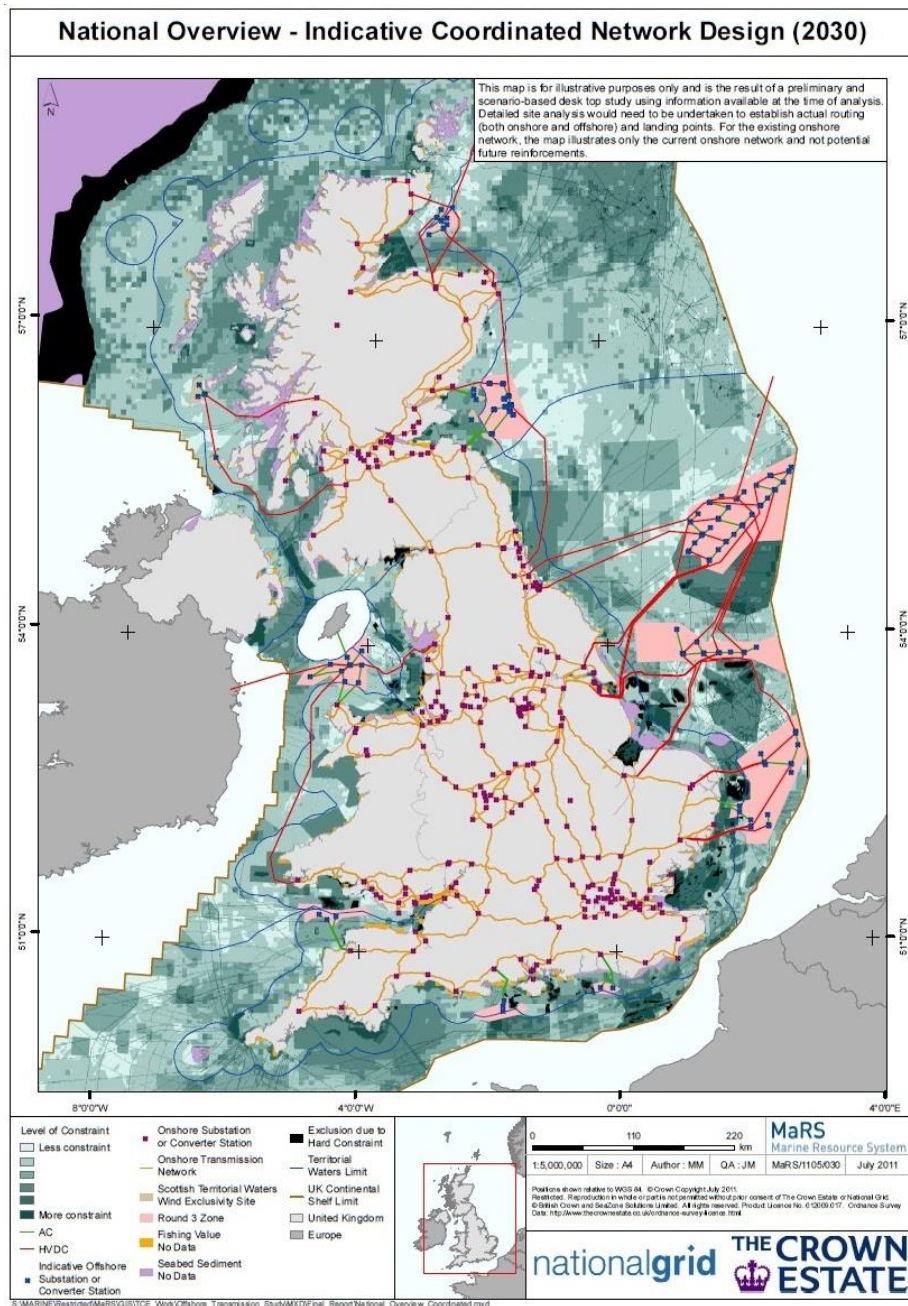


Figure 6.1 showing one of the scenarios the Crown Estate has proposed for offshore grid development.

To relate to this example in Scottish waters, the Shetland (not shown in Figure 6.1), Orkney, Moray Firth and Firth of Forth/Tayside offshore points were added to the landing point dataset. This dataset already contains many east coast landing points, and was not expanded to include onshore landing points, as the report suggests upgrading existing landfall points, that are generally represented in the landfall dataset. The aim of this illustration is to show a change to the offshore distribution. The offshore points are as follows:

Offshore Location	Latitude/Longitude	DTI Water Depth
Shetland	59 53.000 -1 35.000	96 m
Orkney	58 53.000 -1 35.000	100 m
Beatrice North	58 23.889 -2 21.663	61 m
Beatrice East	58 10.000 -2 27.000	57 m
Beatrice West	58 9.000 -3 10.000	57 m
Cullen	57 48.000 -2 45.000	68 m
Tayside	56 26.000 -2 21.000	35 m
Firth of Forth	56 15.000 -1 35.000	49 m
Edinburgh	56 5.000 -2 17.000	53 m

Figure 6.2 showing the offshore points added to the landing point/connection dataset.



Figure 6.3 showing the plotted offshore connection points.

To aid the results analysis only 6 devices were used in this illustrated example. These included 3 wave devices: Wave Dragon (Device 4), Pelamis (Device 5), PowerBuoy (Device 26) and 3 tidal devices: Marine Current Turbines (Device 46), Hammerfest Strøm (Device 56), Tidal Generation Limited (Device 64). From the initial testing runs,

some of the data entries have been updated to represent fresh information that has been gained since the initial technological review was completed. In particular this includes:

- Wave Dragon (4), minimum and maximum water depth extended, and distance to land set.
- Pelamis (5), minimum and maximum water depth extended.
- PowerBuoy (26), wave and tidal regime added, distance to land and tonnage set.
- Marine Current Turbines (46), minimum depth and distance to land set.
- Hammerfest Strøm (56), minimum and maximum water depth set. Tidal regime increased and distance from land set.
- Tidal Generation Limited (64). Tidal regime and PTO set.

In short these alterations were expected to increase the likelihood of all 6 devices finding suitable sites. In the previous testing at *Chapter 5*, only device 5 (Pelamis) passed to a final profit/loss indication without alteration. New devices (from the testing) have also been used for this illustration (which is not linked to the earlier testing) to demonstrate further the operation of the model.

For this example, the HVDC cable option was also removed due to the earlier realisation regarding the extensive distance capability of this cable in relation to the size of the study area, that would ultimately make data analysis more difficult. If the HVDC option were not removed, offshore sites potentially would have changed cable type, rather than showing as a new site. This is because the HVDC cable can reach any site in the study area from the current landing point dataset.

6.2 Model run before and after proposed grid upgrade added to database

Since the device input data has changed from the testing undertaken in *Chapter 5*, a model run was undertaken before and after the additional connection points were added. The first set of results therefore act as the benchmark for this illustrated example. The additional connection points and subsequent model run generate two sets of results that can be directly compared to see how the additional points change the distribution of devices, and their economic indicators.

6.3 Model results and comparison of before and after model results

The results from the both model runs can be seen below in *Figure 6.4*

	Run 6.	Run 7.
Device 4 (Wave Dragon) 33kV	55	55
Device 4 (Wave Dragon) 132kV	27	27
Device 5 (Pelamis) 33kV	186	188
Device 5 (Pelamis) 132kV	87	86
Device 26 (PowerBuoy) 33kV	13	13
Device 26 (PowerBuoy) 132kV	13	13
Device 46 (Marine Current Turbines) 33kV	2	2
Device 46 (Marine Current Turbines) 132kV	0	0
Device 56 (Hammerfest Strøm) 33kV	4	4
Device 56 (Hammerfest Strøm) 132kV	0	0
Device 64 (Tidal Generation) 33kV	5	5
Device 64 (Tidal Generation Limited) 132kV	0	0
Valid count	392	393

*Figure 6.4 showing the relationship between the data in the sixth and seventh runs.
There is only 1 new sites identified.*

As expected all devices entered returned a valid result. However, on comparison of the two datasets it was found the results were disappointing, in that only 1 new site (in Shetland) was found for the Pelamis device, and one site changed from a 132kV cable to a 33kV cable as there was a closer connection point. There was also a very slight decrease in the cost indication (3 sites lowered) from run 6 to run 7 for sites in the region of the new Shetland offshore connection point.

On analysis of the data, it was discovered the user defined distance to land set for the devices was a major limiting factor, that is, the offshore connection points were not going to find new sites as the connection point distance was beyond the distance capabilities set for the devices.

6.4 Further changes to input data with resulting site outputs

In order to find the true effect of the new offshore connection points, a higher figure of 70 km was set for the distance to land for all 6 devices. The model was then run again before and after the offshore landing point additions. This change had the following results shown in *Figure 6.5*.

	Run 8.	Run 9.
Device 4 (Wave Dragon) 33kV	145	145
Device 4 (Wave Dragon) 132kV	64	67
Device 5 (Pelamis) 33kV	325	333
Device 5 (Pelamis) 132kV	660	674
Device 26 (PowerBuoy) 33kV	32	32
Device 26 (PowerBuoy) 132kV	23	23
Device 46 (Marine Current Turbines) 33kV	2	2
Device 46 (Marine Current Turbines) 132kV	0	0
Device 56 (Hammerfest Strøm) 33kV	4	4
Device 56 (Hammerfest Strøm) 132kV	0	0
Device 64 (Tidal Generation) 33kV	5	5
Device 64 (Tidal Generation Limited) 132kV	0	0
Valid count	1260	1285

Figure 6.5 showing the relationship between the data in the eighth and ninth runs.

As expected the model has found new sites with both Device 4 (Wave Dragon) and Device 5 (Pelamis) as a result of the additional connection points. Pelamis had the greatest share of the 25 new sites found.

To identify the new sites effectively, only the new results were viewed by extracted the difference data from run 9 compared with 8, shown in *Figure 6.6* below. The connection points are also plotted with the run 9 results, to show the relationship between the connection points and the newly found sites.

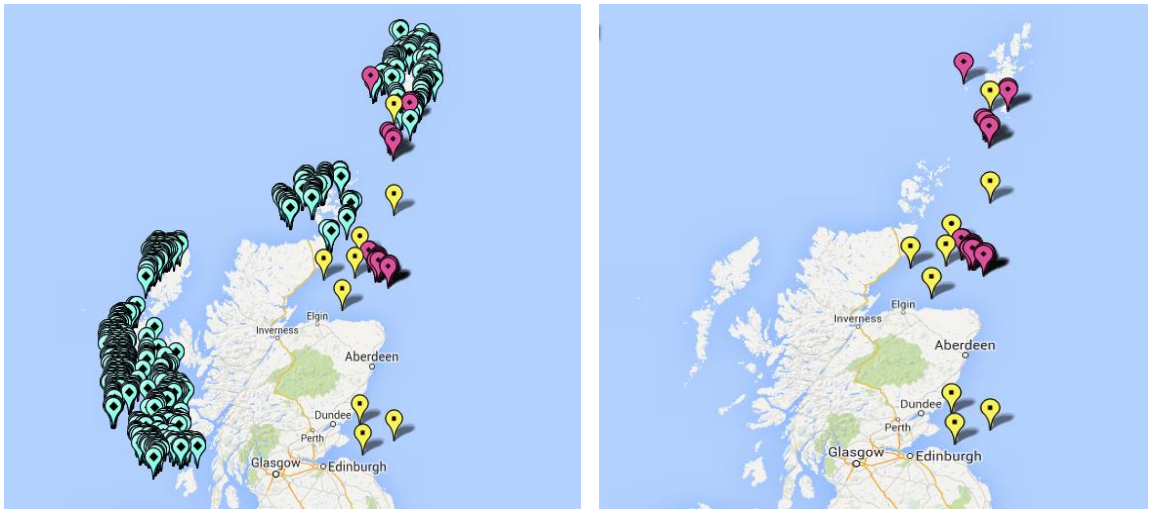


Figure 6.6 showing the valid results for run 8 (left in turquoise only) with entire results for run 9 (additional new sites shown in red). On the right are the newly found sites for run 9 only. Note the new connection points plotted in yellow.

The data analysis can be taken further to show how the connection points affected each device.

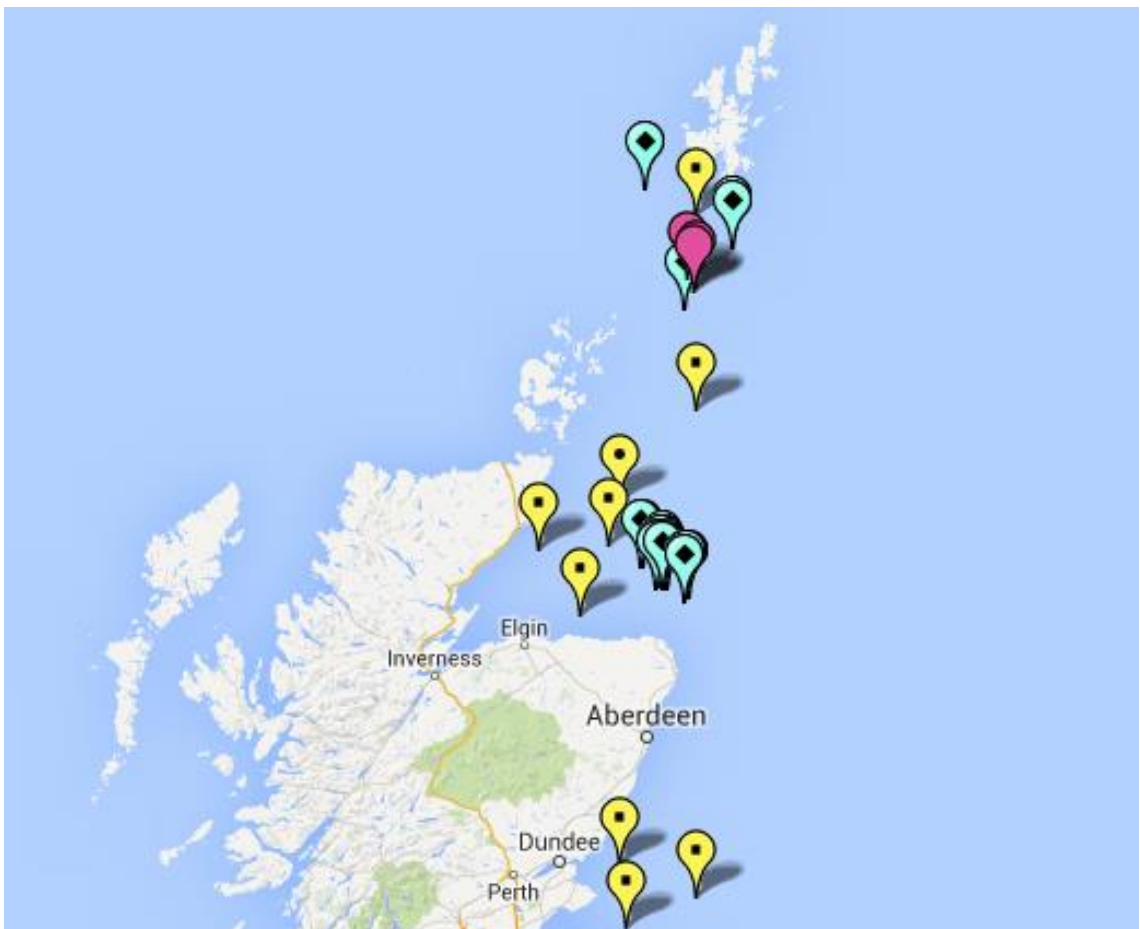


Figure 6.7 showing the specific new sites found for Device 4 and Device 5 in relation to the connection points added. Device 4 in pink, Device 5 in blue, with connection points in yellow. Note no new sites were found in relation to the sites added around the Firth of Forth/Tayside.

Wave Dragon and Pelamis were the only devices that were able to find new sites. The remaining wave device (Device 26 Power Buoy) did not return any new sites as a result of the new connection points. This can be explained by looking at the parameters sets for the device which allowed a lower return in general. Device 26 had a 30 m depth specified meaning only sites exactly 30 m could be considered. The offshore landing points were all in relatively deep water (see *Figure 6.2*) meaning the changes had no affect on the valid sites found.

The 3 tidal devices also did not return any new valid sites. This can mainly be explained by the low tidal resource around the offshore connection points. If a connection point was added in a higher tidal resource, the results would have been different. In addition, all the offshore landing points have a relatively high wave resource which the model does a check for, and will rule out for tidal devices.

The connection points in the south around the Tay and Forth did not allow for any new sites as the wave and tidal resource was not adequate. This can be confirmed by looking at the resource in the user method and by earlier testing when a hypothetical test device with favourable attributes set also did not allow any results in this area, see *Figure 6.9*.

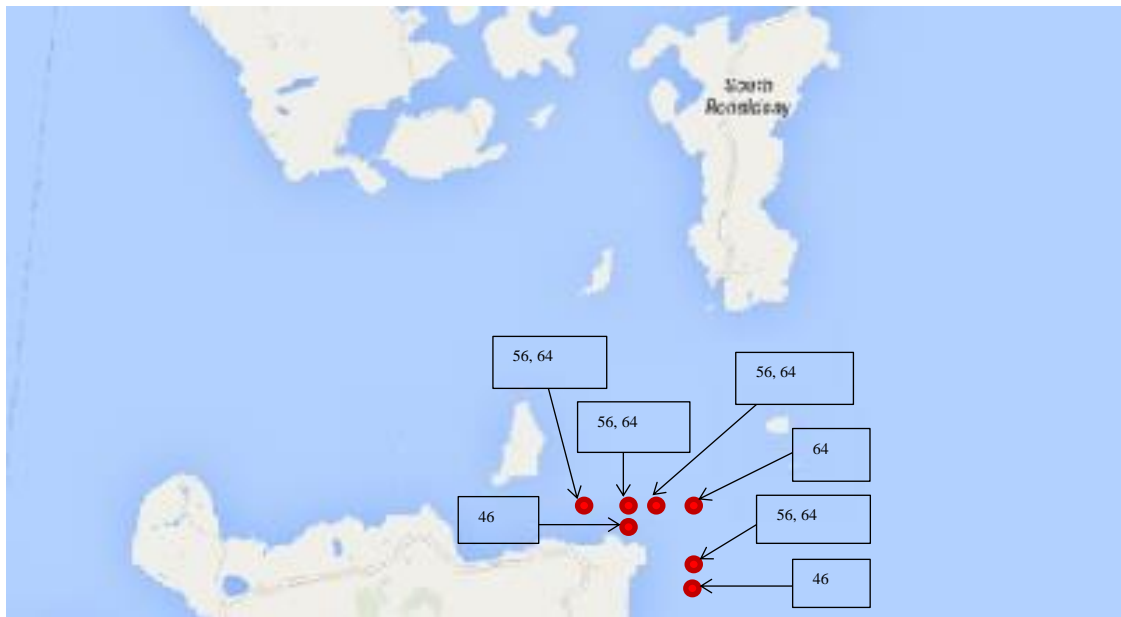


Figure 6.8 showing the valid sites for the 3 tidal devices, Devices 46, 56, and 64, which are all in the same area of the Pentland Firth. This distribution did not alter after the addition of the new offshore connection points. Note that in 4 of the above locations more than one device was found at the same site.

6.5 Economic distribution

There was also a very slight change in the cost distribution with an expected fall in run 9 with 2 sites showing a lower cost indication, and one other site changing from a 132kV to a 33kV site. Although a cost reduction was expected, a more marked decrease was expected.

This is for several reasons. To explain the results, the method used to identify the change first has to be understood. Only sites that appeared in run 8 and run 9 can be compared for an economic change. If we look at the east coast area in run 8 there were very few east coast sites identified in the first place as the higher resource required was further offshore, beyond the capabilities of device and cable. The new connection points alleviated this problem in run 9 and new sites were found. However, since there were few east coast sites in run 8 there were very few sites to compare economically in run 9 as most of the east coast sites were new. The sites that did show a reduction are shown in *Figure 6.10*.

This reasoning can further be confirmed by looking at the previous fourth and fifth runs where a hypothetical wave device (Device 75) had favourable parameters set which did allow for offshore east coast sites. An addition of an offshore connection point (in the Moray Firth area of the North Sea shown in *Figure 6.10* as the most easterly yellow plot) did allow for a significant economic change in distribution for this area, as there were available sites for comparison in both run 4 and 5. *Figure 6.9* shows the distribution for Device 75 during these previous runs.

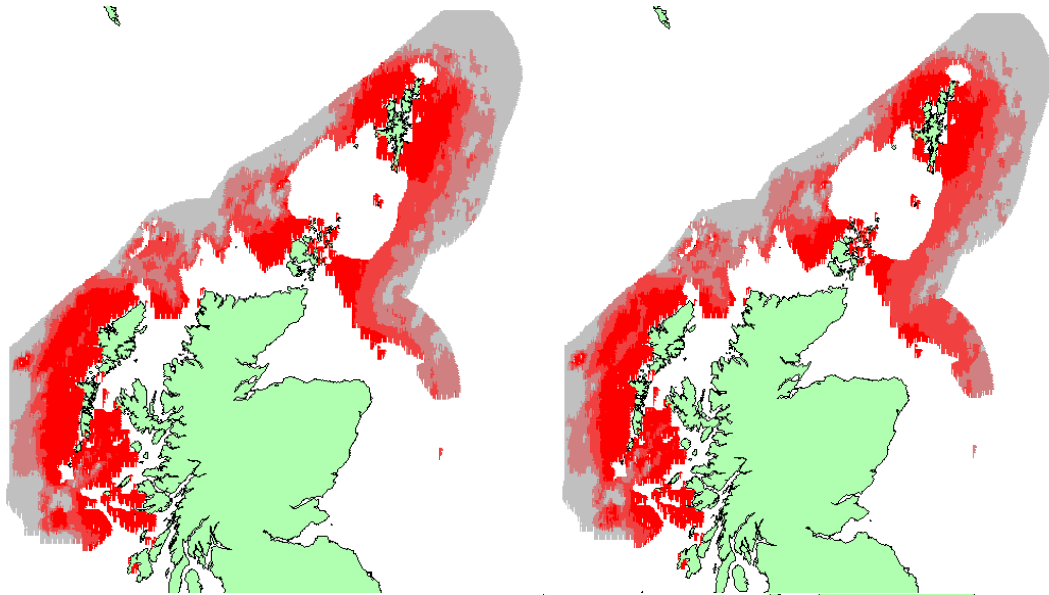


Figure 6.9 showing an overall distribution of Device 75 for the fourth (left) and fifth runs. Note the lack of sites found in the south east for this hypothetical device set with favourable parameter data.

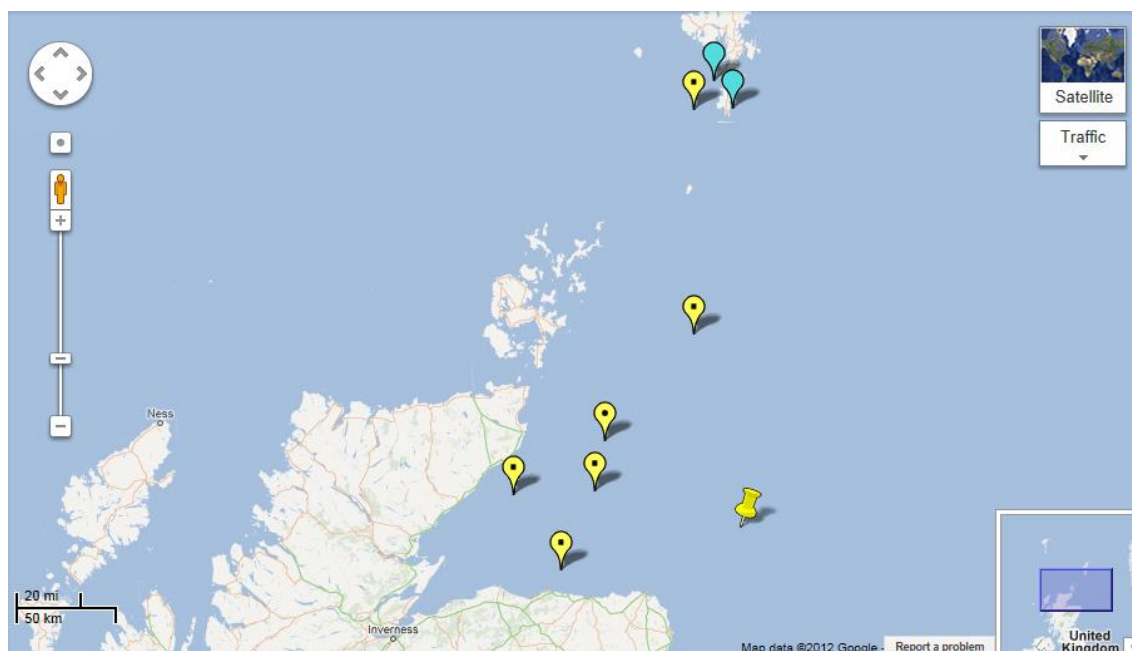


Figure 6.10 showing the 2 sites in Shetland (blue) that experienced a lower profit loss result as a result of the new connection points which are shown in yellow and black. The other yellow plot is the offshore connection point added in run 5 that allowed a significant reduction in cost with the hypothetical device which had a favourable water depth and distance to land set to allow offshore sites to be found.

There are other important economic considerations with the addition of offshore connection points. Although a connection point will become available with a low cable cost (due to decreased distance) the water depth is likely to be higher for new sites, and distance to port further so the installation/decommissioning costs will rise. Many of the values in the database are mainly test values or values gained from other industries which may not show the true trade-off between such changes, i.e. fully understanding the scale between the various cost sets in the database. Therefore newly found offshore sites will be higher even with the new connection points, when compared to sites closer to shore with a similar distance to a connection point.

As the illustrated example did not check the load capacity availability of onshore connection points (which will be an important consideration as most onshore connection points are likely to be running at capacity) the true distribution of the newly added connection points was not shown. This is considering the model checks for the closest landing point which will likely have no capacity available, these values were artificially set to allow the model to proceed. Therefore, the new offshore connection points may have been the closest point with spare capacity. To carry out this logical test the landing points without spare capacity can be reset to reflect the actual capacity. Removing landing/connection points without capacity from dataset would also have the same effect. This action would have a marked effect on the sites found, with Shetland site for example likely not to appear due to the lack of spare capacity.

6.6 Overall findings

From the illustrative example undertaken there are several key points that can be made:

- Changes made to the device dataset (with new information) had a positive affect in that each device returned valid sites. This can be seen further when comparing the

testing undertaken in *Chapter 5* where Pelamis (in smaller numbers) was the only device to have returned a valid site.

- The various model logic worked as expected. The distance to land test for example prevented new sites being found even when offshore landing points were added.
- The addition of the offshore landing points had a positive result for devices that would allow this change, in terms of the device having suitable attributes such as distance to land. This allowed sites to be found further offshore.
- With the addition of the offshore landing points (in this illustration and previous run 5 example) the economic distribution of the valid sites has changed, lowering the cost for site development.

CHAPTER 7 – HOW THE MODEL COULD BE IMPROVED

Although a working model has been produced, it does not claim to be complete. The ideal model was presented in *Chapter 3*, however this was impractical to build mainly because of time and available data. From the ideal design a working model was produced and one that can be readily extended in order to get closer to the ideal model.

This chapter describes in detail how the model could be improved, and is structured to reflect the sequence of steps undertaken:

- A list and recap of the missing constraints and functionality omitted from the as built model from the ideal model design, (7.1)
- Improvements that could be made to the data and program resolution, (7.2).
- A full description of the further functionality (over and above originally designed for the ideal model) that can be added such as: logical detail, data addition, result data management, human computer interaction, economic features, cabling modelling, pipeline and shore station modelling, hydrodynamic modelling, automated automisation, and automated data formatting. (7.3)
- Feedback and possible future usage of the model (7.4).

7.1 Missing constraints and functionality

The as built model is only a working representation of the ideal design and omits some of the constraints analysis and functionality. The elements that were removed to construct the working example of the model are essentially detail, as the main structure stayed in pace with, albeit at a much higher level. As a recap, the idealised list of datasets identified to construct the ideal model was as follows:

- Resource data such as wave, tidal, and wind.
- Bathymetry.
- Other physical data such as geological data to confirm the condition of the seabed and so on.
- Areas of high vessel density associated with narrow channels and shipping.

- Offshore structures such as in the oil and gas industries and their associated pipelines, safety zones and so on.
- Offshore electrical and telecommunication cables.
- Wrecks and other marine archaeological sites.
- Former dumping grounds and contaminated areas.
- Military zones such as training areas and bombing ranges.
- International shipping lanes and areas of high vessel density.
- Fishing grounds and aquaculture.
- Offshore wind (various deployments and leasing rounds), and of course other MEC developments.
- Other activity areas and licencing.
- Other marine resource extraction such as marine aggregate dredging.
- Areas of high recreational use.
- Protected and special sites, such as: Special Protection Area (SPA), Sites of Special Scientific Interest (SSSI), and Special Areas of Conservation (SAC), National scenic areas, RAMSAR (Convention on wetlands) sites, Marine Nature Reserves (MNR), National and Local Nature Reserves (NNR/LNR).
- Areas close to protected sites where the designation includes mobile species such as seals and birds.
- Other environmentally valuable sites (that are not officially designated), such as: maerl beds, reefs and so on.
- Breeding areas for: birds, seals, cetaceans and fish such as herring spawning areas

For the working model bathymetry, resource data (wave and tide) and distance to land were essential features to include. These allowed the basics of a model to be built as these are constraints that can technically prevent a development. The other constraints may not prevent a development, but rather create a problem that will be different for each device.

However for an accurate development appraisal to take place, many site constraints (the development risks) will need to be known. These constraints will determine the likely route through the planning and consents process, as well as give an indication of any device redesign (such as moorings for example) and any additional costs.

The way in which the model would handle these additional datasets is essentially the same as the constraint methods already in place. For the constraints that would not stop the development from a technical point of view, the model would not rule out that site as it does with the current physical constraints. Rather, the model would show that a constraint exists and determine through logic (using methods to compare the device datasets against constraints) the increased risk. Obviously if many constraints exist, the overall development cost will increase proportionately. Each constraint will pose a different risk to a particular device and it is only a matter of adding in the additional constraints data and any particular logic to test the particular constraint against a device. An example here would be to compare a device mooring with the geology at a particular site.

The economic appraisal and cabling methods of the working example were scaled back significantly from the original ideal design. This is mainly in terms of detail, where levels of additional costs (maintenance, finance etc) and revenue (ROCs and other financial incentives) calculations were only carried out at a high level. The original ideal design would allow for more accurate cost and revenue values such as adding discounts rates for Discounted Cash Flow (DCF) to give a Net Present Value (NPV) of the project. The Internal Rate of Return (IRR) could also be generated at this point, which in turn would improve the accuracy of the overall profit/loss indication. Thus it would be beneficial for these original designs to be implemented, but this in time will depend on more data being available for each device.

The original model was also conceived with a hydrodynamic function. This was to determine the most efficient packing density of an array development by calculating energy losses and turbulent effects of an array. A fuller discussion on packing density is detailed at: *A.8 Calculate the number of devices required and device output at a given site.*

The hydrodynamic function would allow a more dynamic look at surrounding sites to be added so that cable requirements (in particular minimum output from a device array) does not force high packing densities on a particular site, as presently experienced with the working example. Therefore a single site may actually turn into several sites to fit the number of devices required to satisfy the cable specification. The design specification of the hydrodynamic model (and sequence within the ideal model) is

discussed in *3.5.1 Finding a valid site*. Alternatively the model could handle hydrodynamic data as inputs which is discussed at *7.3 Further functionality*.

Many of the self constructed datasets were setup with future modifications in mind, with many datasets containing additional data that is not processed by any logic, such as additional device statistics and parameters. Some of these were setup before the decision was made not to undertake the ideal model but are available for future use.

7.2 Data and program resolution

The data included in the working model has been proven to be at a resolution much too coarse to provide adequate results, particularly inshore sites and areas with narrow tidal channels. This was a downfall partly of modelling an area the size of Scotland and her seas, and partly of the resolution of the available data.

An improvement would be data at a finer resolution. The model design allows smaller areas (such as the Pentland Firth where the volume of fine resolution data are increasing) to be added without any redesign of the model structure or code. The model could work at various resolutions, providing say a regional and nested localised view where data exists. Either the regional model could be run in order to find areas of interest which could be studied in more detail with finer datasets, or the model could run to the resolution of the finest dataset. The latter could be implemented by either converting all datasets to the finest dataset before processing by the model, or by the model checking the resolution of each dataset and reading the closest value (or by using methods such as interpolation or kriging) at any given location for datasets at a lower resolution. This would allow datasets of various resolutions to be processed at the same time.

7.3 Further functionality

There is simply not room to discuss all possible additional features and functionality, however some of these are considered further below.

7.3.1 Logical detail

There can be many improvements made to the functionality the code provides. One such example, as already shown, was the improvement made to the logic after the first initial run of results. The resource methods were modified so that the logic discarded any significant wave sites with large tidal resource and vice versa. This is an example of significant improvement to the logical function of the model which was done with an insignificant alteration to the code. This is the sort of logical detail (programming tasks) can be extended within the data structures that already exist. This example can be taken further as it would be a beneficial addition if the opposition tidal/wave resource could be controllable i.e. a switch option to turn on or off, and increase or decrease the tolerance value so the differences can then be analysed. This in turn would depend on a better understanding of how wave and tidal current interactions affect each device. There are many other improvements that can be considered, such as improving the logic used for distances between points in the model.

7.3.2 Data addition

Within the working model there are a lot of record entries that are not complete. Device datasets is a good example of this, as many of the key factors of a device have to be known in order to allow the model to proceed. The more complete the valid data used, the more accurate the final result. In the case of devices, many identified devices are not considered by the model as key features are not known. If they were known, the results are likely to have been different as shown in earlier testing (*Chapter 5*) by experimenting with altering (and adding) input values for devices.

Since the various model test runs were undertaken for this thesis, there has been the release of several new devices. The industry is moving extremely fast at present, and there are new designs from existing and new companies emerging on a regular basis. It would therefore be beneficial to keep the device datasets up to date and run the new data through the model as soon as it is obtained.

7.3.3 Result data management

The model, as described, has a results function where the valid results can be displayed in various lists. However, without various computing (and in particular database and GIS skills) then the results at present are not easy to visualise. It is quick and easy to discover the best site for a device and cable and so on, however, to actually change one data field within the database and see how this affects the distribution is not so easy.

This is only possible at present by working with data outputs with other tools such as GIS. However, an in built GIS display system would make this sort of result viewing much easier. This would be more beneficial than using database queries and program scripts for example to find the differences in result datasets, which ideally need to be plotted into other tools. This consideration is particularly important if the model is to be developed and used by an end user that may not necessarily have GIS, database or other general programming skills. To keep with the open source theme of the project, an automated Google Earth/Maps output would be priority during this work.

7.3.4 Human Computer Interaction (HCI) considerations

From a user point of view improvements could be made to make the entire application more user friendly. This applies to use of the underlying database, right through to analysing the final results.

The database that is used to store many of the datasets the model uses, is at a basic level in Human Computer Interaction (HCI) terms. There is no Graphical User Interface (GUI) associated with any of the base datasets which makes appending or editing data slightly more problematic if the user was unfamiliar with database record sets.

Therefore, standard Windows GUI tools and functions would make viewing, appending and editing data in the database more straightforward.

The same argument applies here to the various inputs and outputs the model is working with. The current setup is to process one collection of data at one time, which has to be predefined in the database. The model can only process one collection of data at a time, outputting one set of collection output files from predefined input data. The current procedure to switch between the input and output data locations is logical in terms of a

user with computing/programming skills. However, the model will over a period of time ideally work with multiple data collections, that is, provide a GUI selectable option for the user to load for input, and where to save the output files. This would eliminate the need to change any database or code entries, and the names of files and directories.

The model output files could also be formatted automatically to other software standards such as MapInfo, Google Earth and so on. This would allow the results to be loaded and viewed more easily.

7.3.5 Economic features

Over and above the ideal design there are several additional economic features that can be added. One such example could be the addition some economic controllers, where scales and thresholds can be set, such as for a project budget. This could take the form of another filter in the overall equation that could be also be used to turn on or off spatial results, if profit/loss over (or under) budget, or specified internal rate of return.

There are many more additional economic features, techniques and methodologies that could be used to expand the economic functionality of the model. Another such as example would be to include economy of scales for a MEC development.

7.3.6 Cable modelling

The current cabling method could be expanded to include additional functionality and therefore a more robust cable selection method. There are many considerations such as:

- Cable configurations. This is a new and developing technology for the marine energy sector and MEC cable methods cannot be realistically compared to other cable projects, other than offshore wind at present. Information from the wind industry is hard to establish, as each project is unique. There can also be added logical detail to include various configurations for the same site, the as built model only considers one ideal cable configuration determined by cable distance. However, it would be valuable to compare various different configurations at the same site.

- Routing algorithms, the site to shore will not be a straight route as assumed at present, and therefore all distances will most certainly be longer. Additional algorithms will also be required to work out the cable length (and therefore cost) to link up each device within the array. There will also be the need to look at the cable route in terms of constraints (physical and non physical) that may prevent a cable deployment, or increase the cost. This can be achieved by comparing the site constraints against the cable in the same way the model compares the site constraints against a device.
- Cables may need to be buried/spanned/armoured in various areas.
- Specific devices will require specific solutions, affecting installation costs.
- Grid tariffs, such as firm and non firm grid connections and connection charges.
- Additional onshore requirements such as routing, available capacity throughout the network etc.

To include this level of detail, a separate project or sub model could be incorporated into the overall logic of this project on completion. This is consistent with the overall design, as the overarching model basically sits on top of many sub models (functions) that all have specific tasks. A sophisticated cable model could be developed independently and brought into the overall model to work with the other existing sub models.

7.3.7 Pipeline and shore station modelling

Since not all the devices convert extracted energy to electricity offshore, there will be need to cater for devices such as the Oyster that uses an offshore pumping system to drives an onshore hydroelectric system. For this category of device, a pipeline model would be used instead of an offshore cabling model, which share a similar methodologies, such as distance, device capacity, route, price per km and so on. A further method could also be added to locate suitable sites for onshore conversion stations. This will be an important consideration to identify these terrestrial locations, as well as having a bearing on many other variables such as the offshore distance calculations.

7.3.8 Hydrodynamic modelling

Another benefit to the model would be the inclusion of a hydrodynamic model as discussed previously. However as hydrodynamic models are a very specific product, it may be beneficial to use hydrodynamic data as an data input much in the same way as the cable sub model.

The main overall advantages of including a hydrodynamic model are discussed at *7.1 Missing constraints and functionality*. Providing a robust hydrodynamic model would allow a great deal of additional functionality to be developed, such examples include:

- Predictions of actual wave and tidal resource at any particular site, including tidal cycle.
- From the above example, if we consider the tidal resource in more detail and in particular the resource through the water column. The velocity will vary significantly from the surface to the seabed, which is understandably difficult to model considering each site is likely to be different. The DTI data tidal power is calculated for the upper (50%) of the water column.
- Selection of tidal devices, as well as where they could be placed. Following on from the resource through the water column modelling, ideal rotor dimensions at any given location can be determined. The converse is also true as the model could answer the question: how significantly would a particular device need tailored for a particular site?

7.3.9 Automated automisation

The model could also be automated with the inputs required to find favourable results determined iteratively by code that is integrated in the application. This would work along the lines of running the current batch program, and when results for devices and sites do not pass, then the model could review and record the critical values as a form of sensitivity analysis. The model could loop around to test the critical values again which would ultimately give a set of values (in separate data output files) that a device would have to possess if it were to produce a valid profit/loss indication.

The output would be a significant volume of files which would have to be analysed in an automated fashion, giving more work to the result data management function of the model.

7.3.10 Automated data formatting

It would also be beneficial to construct a software tool to automate further the data formatting processes. With any programme logic, there is a desired format for input data, so the task would be to set up a tool to format any kind of data to the input specification. This would require a significant amount of code and logic, however it would allow more external datasets to be quickly converted for the model to use. A software tool of this kind would also have the functionality to turn non formatted spatial data into such for the model's benefit. The integrated tool would be used to convert data into the model format before future modelling, and therefore not need to be undertaken within each model run.

7.4 Feedback and possible further usage

At this point in development, it would also be beneficial to take the work produced to industry for feedback, i.e. what would a developer or planner like the model to do, and what would they see as a logical development path.

In general it would also make sense for the model to be used from a user/planner point of view rather than a software developer point of view, to find out exactly what it can show us. The model has been developed to carry out a specific set of logical tests and some of the results have been analysed, however, it has not been trialled by others to any great extent. Therefore, it would be beneficial for the model to be used over a period of time, putting it to the task it was designed for (indicating where MECs can be deployed). It is also more than likely that different users would wish to tailor the model to a specific purpose, depending on their particular priorities.

With model structure in place, there is potential to add functionality and additional data to analyse shoreline devices. This is also true of other forms of technology such as offshore wind as the methodology is transferable. The model could also be set up to produce dataset layers to aid zoning and therefore act as inputs to a conventional marine

spatial planning tool. It could also be set up to address onshore spatial planning questions within the terrestrial environment.

CHAPTER 8–DISCUSSION AND CONCLUSION

One of the main stated aims of this research was to produce a site appraisal model that could provide a more dynamic and efficient approach than currently available through convention Marine Spatial Planning (MSP) approaches. MSP, through techniques such as constraint zoning, unnecessarily rule out no go zones, which could be more effectively treated as developers risk, even in protected areas. As a result of zoning “free space” is identified which may be inappropriate for MEC development as various criteria (such as resource) may not exist in this free space. A model was necessary to show the valuable sites to MEC development, highlighting where the pressure would be to develop with the available resource, grid, technology and so on.

An idealised predictive model was designed to achieve this aim. However due to time constraints and lack of data for the overall study area this design was not feasible. A working model was produced with a framework that can be expanded to encapsulate all aspects of a fully functional model. The data and functionality omitted from the full model design can in most parts be easily be assimilated to the working model and therefore can be upgraded in stages. There are new and improved datasets available at present (and continue to become available) that there was not time to include. This is also true of functionality such as the various economic calculations that can also be added with ease, although unknown aspects such as maintenance and weather window are likely to remain problematic. It was acknowledged early in the project that the ideal model could not be built, however it was important to design the model in its ideal form, and produce an overall scaled version rather than concentrating on smaller aspects. Therefore, a working example was successfully constructed to demonstrate and confirm the overall methodology.

Although the model produced is only a working representation, the functionally included has shown to be extremely flexible and powerful. The construction of the application is such that technologies, cables, landing points, ports and so on can be added, amended and deleted with ease, meaning this tool can interact with a significant number of variables with no intervention from the user once set to run. This allows the model to be run with varying input data very effectively, and has shown to have a significant affect on the output results. This dynamic approach allows any stored value to be changed, which depending on the value’s significance will have an affect on the

overall physical site and economic distribution. This was highlighted in the various testing and illustrated examples where several small changes to device parameters, and the inclusion of new landing points had a significant change in the resulting distributions.

The resulting tool, although designed to be used for developers and investors, provides improved information to the planners than resource maps do at present. Additionally it is able to provide information if circumstances change in terms of grid capacity, cabling and technology which will be of significant benefit to the industry. For example a technological neutral company can use the model to determine which method would best suit a site. The industry is in an early uncertain stage with no clear indication of which technology (in terms of MEC, cabling, grid solutions and so on) is best suited to the emerging marine energy problem, so a dynamic tool is required to give an indication of what the best technology is to use. This is an important feature as this development appraisal approach allows easy identification of potential commercial sites which has not been possible before now.

The research has made a number of recommendations for future development with attention to detail, and more accurate and comprehensive data being the key identified issues. Ideally, the working example should be extended to incorporate the full design. There are also various recommendations to improve the overall model even further with a continued resource. Many development proposals have been documented, only possible due to the foundation laid by the construction of the working model. The level of detail and inclusion of additional datasets can be a continual process as knowledge is gained. There is also the potential to improve the use of the model application and how the results are analysed and presented, which at present is not as user friendly as it could be.

Another key feature of the application model is that it has been developed in various tools all of which are inexpensive to buy. There is an argument that the modelling could have been undertaken in other packages such as IDRISI or ArcGIS, however, it was felt extremely important to keep the work as open source as possible, with the added advantage Microsoft windows products allowing enhanced usability through the various graphical tools that can be used. An executable application file is provided with this thesis which does not need a Visual Basic (VB) compiler to run. If the model is to

be altered the VB development software will be required. However, Microsoft VB and Access (part of the Office suite) are both inexpensive off the shelf products that can be used to develop or amend the model. The full code listings are also available and the code for the batch mode has been documented in pseudo code so that the model can be coded in any programming language. Therefore, the methods and calculations of the model are not only open source, but fully transparent.

Therefore, a powerful tool has been produced that can be used and developed inexpensively. It can also be developed further with off the shelf products or in a new development environment with the documentation provided in this thesis.

This will allow the end user to model various scenarios in a dynamic and flexible way, showing the true power of the model. Although test and demonstration examples have been documented, the true value of this thesis will be shown in the use of the model to help answer complex problems. The model has the potential for much more advanced and powerful operation in addition to its current capabilities, which can be summarised as:

- A more advanced tool for developers, planners and investors using a specific form or technology, or finding a technology for a specific site.
- A beneficial use for organisations such as the Crown Estate and Marine Scotland in identifying with spatial planning economically efficient use of the resource.
- More advanced modelling functionality that is not instantly obvious from the already established design functions above. One such example would be to further understand the conclusions drawn from the recent Ofgem significant code review, which sets out new transmission charging arrangements. Within this report Ofgem reiterates its argument that generators should pay for the costs which they impose on the transmission network, which will inevitably increase project costs on islands (Ofgem, 2012, 2).

There are mitigating principles that have been suggested, such as generic/average cable costs used for islands rather than actual costs to ensure consistency, extension to the Active Network Management (ANM) scheme with charges based on usage rather than installed capacity, re-examining island security factors, and the treatment of expensive HVDC convertor station costs. In short, these can be

considered as complex economic proposals, and their consequences are difficult to quantify without the help of modelling to determine the economic distribution change of such measures.

The model developed in this thesis can be setup to show the economic distribution for each solution (with the economic scenarios catered for by refining the added project costs) and various combinations of these. Various model runs with each scenario would be undertaken to allow a picture of what solutions would work best for a particular area, i.e. show the distribution change with the distributed project costs. The results may show that another solution may be needed for island projects to be economically feasible, such as the idea of island ROCs. Alternatively, the results may show the current system in place will allow some island projects to be feasible as Ofgem are suggesting, or a situation that will stifle growth as feared by industry (Baster, 2012). This is just one example of how the model can be used as economic situations arise. The connection charge issue above is a complex situation that is causing deep concern (Scottish Renewables *et al.*, 2012) with, until now, no easy way to answer such questions.

- Another further modelling example would be to analyse optimal cable connection points. The model could be set up to run in multiple time to determine where the best cable connection points would be in terms of the resource, and also the capacity these would need for different scenarios of development. This would work by running the model from the start to end location geographically to determine the project costs at each location with a new connection point added. Once each location has been calculated, a comparison can be made to test where would be the most economically feasible locations for connection points. Similar tests would also be carried out to indicate the most feasible landfall points, additional landfall points, and landing points to upgrade. There is also the potential for the model to produce random data for many of the unknown inputs. This would allow the integration of Monte Carlo experimentation with the model data.
- The above multiple time functionality, in conjunction with a hydrodynamic modelling element, would also help define the device on device impacts where the resource at each site can be modified considering neighbouring developments.

Therefore, the technique and methodology provided in this research is able to provide the marine renewable industry with a unique site appraisal tool. This will assist technological developers, who can spend their limited time and resource on their devices, rather than trying to identify sites to deploy them. Effective and planned MEC deployment will ultimately help the emerging marine renewable industry achieve commercial energy extraction, and assist Scotland in realising her renewable energy potential.

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IN

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Verdant Power, www.verdantpower.com

Viking Energy, www.vikingenergy.co.uk

Water Wall Turbine, www.wwturbine.com

Waveenergy Denmark, www.waveenergy.dk

Wave Energy Centre, <http://www.wavec.org/>

Wavegen, www.wavegen.co.uk

Wavemill Energy Corp, www.wavemill.com (*No longer available*) now at:
<http://www.zulenet.com/electriceco/wavemill.html>

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World Energy Council, www.worldenergy.org

APPENDIX A BATCH ALGORITHMS AND CALCULATIONS THE MODEL USES

A.1 Determining a spatial distribution for each device determined by water depth

This method checks the device table within the MS Access database which contains a value for the maximum and minimum depth that the device can be placed. These values for each device are tested against the mean water depth from the DTI data. If the water depth in the DTI dataset falls within the maximum and minimum a “1” is written to a data structure which in turn is written to an output file.

If the water depth is not valid then a “0” is written to the structure and output file. The method also checks where the DTI data does not exist around the edges of the matrix (indicated in the DTI data fields as “NA”) and “NA” is written so that output file to stay consistent with the DTI datasets. The output file is at the same resolution as the DTI original, and contains true and false values for locations where devices can be placed spatially. The name of the file contains the device ID so each output file is unique to each device. The logic behind this method can be found at *Appendix J.1* in the form of pseudo code.

A.2 Determining a spatial distribution for each device determined by resource

This method checks the device table within the MS Access database which contains a value for the ideal resource for both wave and tidal devices.

If the device is a wave device, the resource value (its operational power boundary) is tested against the winter mean wave power and the summer mean wave power value from the DTI data. If the device resource value falls within these two seasonal DTI values then a “1” is written to a data structure which in turn is written to an output file.

The same logic applies to tidal devices were the device resource value is tested against the mean spring peak flow and the mean neap peak flow values from the DTI data. Again if the device value falls between the two DTI values then a “1” is written to a data structure which in turn is written to an output file.

If any of the resource values are not valid then a “0” is written to the structure and output file. “NA” is written where no data exist. The output file is at the same resolution as the DTI original, and contains a true and false values for locations where devices can be placed. The name of the file contains the device ID so each output file is unique to each device. The logic behind this method can be found at *Appendix J.2* in the form of pseudo code.

A.3 Determining a spatial distribution for each device determined by distance to land

This method checks the device table within the MS Access database which contains a value for the maximum distance that the device can be placed from land. The device distance to land values are tested against the distance from land value from the DTI dataset. If the device distance is less than the DTI value then a “1” is written to a data structure which in turn is written to an output file.

If the device distance is greater, then a “0” is written to the structure and output file. As before the method also checks where the DTI data has “NA” written values and outputs an according “NA” to the output file. The output file is at the same resolution as the DTI original, and contains true and false values for locations where devices can be placed. The name of the file contains the device ID so each output file is unique to each device. The logic behind this method can be found at *Appendix J.3* in the form of pseudo code.

A.4 Determining an overall spatial distribution for each device determined by water depth, resource, and distance to land

This method takes the results from: A 1, A 2, and A 3 and produces a logical union as a single output file for each device, which shows where each device can physically be placed in relation to the depth, resource, and distance tests. The three results combined together acts like a binary truth table where the “1” values in the datasets act as true and “0” as false. The test within this method is an “AND” logical function (or AND Gate) where the test is only true if all the values are true. If a device at any given location does have a true value for depth, resource, and distance then a “1” is written to a data structure which in turn is written to an output file.

If any of the depth, resource or distance fields hold a false “0” value then a “0” is written to file, regardless if one or both the other values are true. The logic behind this system is that if a device fails on any of the key features then the site is not suitable.

To achieve this, the method opens the three files produced at: *A.1*, *A.2*, and *A.3*, reads each data field from each of the three files from start to finish, and writes to the data structure whether the data within the data field have passed or failed the logical test.

The same principles again apply to the “NA” values for areas with no DTI data, and a file for each device is also output. In theory, there could be no limit to the number of tests like: *A.1*, *A.2*, *A.3* where a constraint could restrict a device. If additional data existed (for example seabed geology) then more tests could be set to produce true and false values, that could then be validated all at the same time under this method (*A.4*) using the above described logic. The logic behind this method can be found at *Appendix J.4* in the form of pseudo code.

A.5 Constructing a distance matrix from each site to closest power station

This method uses the power station table within the MS Access database to construct two outputs files containing the ID and Distance value to the closest power station at each site.

The power station table contains a value for longitude and latitude, and the method holds the values of the west and north boundary. A nested “for loop” (which is a system used on all the batch and file handling methods) works to the boundary values of 450 records and 520 columns and each time an increment is made on the outer record loop, a north count is decremented by the scale of the cell resolution of the file, which in this case is 60 seconds. Each time an increment is made on the inner column loop the west count is decremented by the cell resolution scale which in this case is 90 seconds.

With each record, every power station’s location (in seconds) is compared against the above mentioned north and west counters in order to get a difference value, which is between the current site and power station. These values are then passed to a separate sub method (calculating distance, see *A.17 Calculate distance between two given points*)

which works out the distance from the latitude and longitude difference values, taking into consideration spherical geometry.

Once the distance method has determined the actual distance between the points, the distance is returned. As the method proceeds with each power station to the end of the record, the distance value is updated if a shorter power station distance is found. There is also a logical test to ensure the power stations have enough spare capacity to take the new connection. This is achieved by comparing the overall distance of the site with the corresponding cable length. The cable type can then be determined with its rating, which can be compared with the power station spare capacity. If a valid landing point cannot be found then “na” is written to the dataset.

The same principles again apply to the “NA” values for areas with no DTI data, and a file for device is output. Within this method there is the option within the code to comment out (disable) the logic check condition that checks where the DTI banks exist. If the condition is disabled then the method will produce a complete matrix of values regardless of any DTI data, i.e. the calculation within method operates without the need for the DTI data so the entire matrix of locations can be populated with valid data if required. At present the method follows the DTI format. The logic behind this method can be found at *Appendix J.5* in the form of pseudo code.

A.6 Constructing a distance matrix from each site to closest port

The logic in this method is very similar to that of A 5. The output is also very similar in that a distance and ID is written to two separate output files. The output files in this instance contain the distance at each location to the closest port in the database, with the second file holding the ID of this port at each location within the file. The only main difference in the logic is there is no logical test for spare capacity for ports as there is with power stations. The logic behind the power method can be found at *Appendix J.6* in the form of pseudo code.

A.7 Calculate cable costs for each site against valid location for each device

This method uses the distance to power station output file constructed at A.6 and the cable table within the database to construct a cable cost for each device. The method validates each site (per device) by checking the union result output file produced at A.4.

The cable table within the database contains three distinct cable types with their individual attributes. The three types are generally seen as the three main options for development, depending on the properties of the development, i.e. distance from land, and level of generation. These factors are looked at in more detail shortly, this method is solely concerned with generating a cable cost by using the cost per km from the cable table, and the distance from the program generated distance to power station file. The logic behind this method can be found at *Appendix J.7* in the form of pseudo code.

A.8 Calculate the number of devices required and device output at a given site

This method uses the cable and device table within the database, and the distance to power station output file (produced at A.5) to construct two new outputs files containing the number of devices, and site output value for each relevant cable type, and device.

The devices considered are those that have had passed the union test which is recorded within the output file produced at A.4. Another validation check is performed using the distance to power station output file, which, with the cable table determines if a location is within the range of a particular cable type. If the location is within range for a cable type, for each cable and device, the output from the device is used with the cable's maximum and minimum output loads to determine how many devices would be required to justify the cable at this site. At this point, the maximum and minimum site output can be calculated for each device and cable type at this location. The output and number of device values are written to file in the usual fashion. The logic behind this method can be found at *Appendix J.8* in the form of pseudo code.

With the built model there is a problem with the above logic, in that the ideal packing density can be exceeded, i.e. there is no logic to prevent this eventuality. The ideal packing density for marine devices is somewhat unknown and is different for both

individual wave and tidal devices. However it is an important consideration and is worth some discussion.

The area of a site within the spatial system built is 1 nautical mile from north to south, and 0.666 nautical miles from west to east, which gives an area equivalent to 2.284 km². For the packing density for tidal devices EMEC have set a standard stating that per km², devices are to be spaced 2.5 D by 10 D where D equals the rotor diameter of the device. (EMEC, 2009). This is directly equivalent to 1.25 D by 20 D as suggested by the University of Southampton (Bahaj *et al.*, 2007). Which can be expressed as 1 rotor per 25D² m² (Carbon Trust 2011).

To take an example with a proven device from the database, the Marine Current Turbine (MCT) device has a rotor diameter of 16 m, which would allow 156 devices with the 1 km² area and 356 for the site area defined by this project. However this device has a twin lateral rotor design so this figure would have to be reduced by approximately 50%. For the size of site defined by the model this would mean 178 devices would be allowed, i.e. $0.5 \times (1 \text{ km}^2 / 25D^2 \times 2.284)$. MCT is a 1.2 MW device so the device would not allow a valid 33kV cable as the minimum requirement (within the database) is set to 400 MW and the site would only produce 213.6 MW. However, the minimum requirement for both 132 kV and HVDC cables is 200 MW. This is also the top line figure without taking into consideration wake and turbulent effects which will reduce the efficiency of the device and therefore lower the overall site output.

To take another example, the largest single tidal device at present (the AK1000, claimed by developer Atlantis Resource Corporation) has a rotor diameter of 18 m and an output of 1 MW. This device is not within the database of this research as it was not identified at the time of the technological review. However, if it were added it would return 282 devices per site, as the diameter to output statistic is slightly more favourable in terms of the packing density suggested, and the cable requirements of the database. However, this is of course if the other physical parameters were in the model range.

It is also interesting to note that the newly identified device again would not allow for a 33 kV (400 MW) cable. A full study of all the devices would need to be undertaken (for which the rotor diameter data are sparse) as the minimum requirement for a 33kV cable would be restrictive in terms of the spatial arrangement of tidal energy convertors.

This may also be the case with other cable types for devices with less favourable rotor size to output ratings. It has been assumed the percentage of energy not captured by the turbines due to wake turbulence propagation is between 5 and 20% of the total amount of energy extracted from the system (Carbon Trust, 2011).

It has also been suggested that the farm packing density could be modified to enhance the response of the hydrodynamic tidal system however this remains an emerging science (Vennell, 2010).

For wave devices the methodology for determining the packing density is different with the general convention at present suggesting an output limit per area, as opposed to a spatial restriction. Unlike tidal arrays this value is not agreed with various figures being suggested.

Although it is difficult to determine exactly what this figure might be, there are several sources, such as the Electric Power Research Institute (EPRI) in the United States, and developers such as Pelamis believing the total recoverable wave energy resource is limited to 15 MW per km² (EPRI, 2011) (Pelamis Wave Power, 2012). Another developer Carnegie Corporation, is expecting to achieve 8 MW/km² for the CETO II device which has a rated capacity at 300 kW (Power Projects Limited *et al.*, 2008).

It is however possible that other wave energy developers are aiming above 15 MW/km². AWS Ocean Energy with their current device design (with a capacity of 2.5 MW) consists of an array of 12 cells, measuring around 16 m wide by 8 m deep, arranged around a circular structure with an overall diameter of 60 m. This would therefore mean only 6 of these devices (taking up around 131 m²) in a 1 km² spatial area.

Even with the high footprint of the latest Pelamis device (720 m²) it is debatable if it would be physically possible to place more than 15 MW (20 devices) within the 1 km² area. With the larger site area defined by the model, the output capacity (using 15 MW/1 km²) would be 34.26 MW which converts to around 45 Pelamis devices.

Although it is difficult to find any significant reference to other specific devices that may allow for higher (or lower) densities, there is some evidence that point absorber devices (buoy like structures that tend to have a small footprint, such as the OPT Power Buoy and Wavebob) may allow a packing density of up to 25 MW per km² (Power

Projects Limited *et al.*, 2008). This in the model spatial terms would allow 57.1 MW per site, which is still short of the lowest cable output requirement (200 MW) of the model.

Therefore, the current packing density creates a significant problem for wave devices (and to a lesser extent tidal devices) to the current set up of the model. That is, with the current cable range values, no wave site would be able to allocate a valid cable type. The cable data used were adopted from the offshore wind industry as there were no examples available from the wave and tidal industries.

Therefore, for the allocated size of the wave site, the cable options would have to be more flexible (that is, lower ratings) or adjacent sites would have to be joined to adjacent valid sites in order reduce this problem. The values in the database for cables can be relaxed to take this into consideration. It is likely, as cable technology continues to mature, specifications will become more realistic for wave energy developments and that additional cable types will continue to be developed.

The logic to look at adjacent sites is possible with expansion of the loop structure of the design. This would take the methodology if one site did not allow a high enough output, then testing of the adjacent sites would be carried out to identify an adequate resource. Some of these sites will obviously fail as they will not match the other criteria set by the model (depth, resource, distance to land) so it still may not be possible to identify a suitable development area using this method.

The logic for identifying adjacent sites would start with the 8 “connecting” sites and work outwards, i.e. if we imagine our initial site is in the middle of a block of 9 sites. If the 8 adjacent sites did not allow a high enough output, or one too many of them did not pass any of the other model criteria, it would be wise to set up some boundary rules, so that further sites outwith the block of 9 could only be tested if they were connected to the original site. As an example, if only 1 out the example block of 9 sites was available then only sites that were adjacent to the new valid site could be considered. However this could be modified with additional logical rules if required.

12	13	14	15	16
11	2	3	4	17
10	9	1	5	18
25	8	7	6	19
24	23	22	21	20

Figure A.1 Showing a matrix of a search area of valid (green) and red (invalid) sites. If the originating site is 1 (that cannot fulfil the output required for a valid cable type) the search would test adjacent sites such as 2, 3, 4, 5, 6, 7 and 8. If these additional sites still did not produce the desired output, further sites could be tested, although it is likely some boundary rules would exist. In the example above only sites directly connected spatially are considered to be valid (green) i.e. the connected sites can make up one continuous arrangement.

As with tidal devices the optimal layout and packing density, wake and other effects between wave devices is uncertain. There have been suggested power losses of up to 5% through wave array effects, although the Scottish Executive believe this figure is only around 1% (Scottish Executive, 2006).

A.9 Calculate the device cost for a given valid site

This method calculates the capital cost of valid devices at any given location by using the device table in the database and the number of devices required data file produced at A.8.

The device table has an entry for the capital cost of an individual device which is calculated mainly from the base materials used to construct the device, i.e. the material cost per weight, percentage of the materials that make up the device, and the device tonnage.

With the cost value, this is used with the maximum and minimum number of devices per site, to produce a total device cost. The outputs from this method, are the valid devices, with the maximum and minimum device cost for each cable type written to file

in the usual fashion. The logic behind this method can be found at *Appendix J.9* in the form of pseudo code.

A.10 Add device costs to cable costs

This method produces a cost for the cable and the device at a valid site, with the cable cost output file produced by A.7, and the device cost output file produced by A.9.

The two previously produced output files are used by this method as input files, with their values added together and written as a file containing the cost for both the device and cable at each location in the usual fashion. The logic behind this method can be found at *Appendix J.10* in the form of pseudo code.

A.11 Calculate revenue at each site for each valid device

This method produces an output file containing the revenue gained by using the model data table in the database, and the number of devices required and device output at a given site file produced at A.8.

The database holds the record set which contains various data that are used by the model, this method calls on the unit price of electricity field which is used with the rated output at each valid site with the number, and design life of each valid device, giving a revenue figure which is written to an output file in the usual fashion. The design life of the device is also validated and if a value does not exist then a default value from the model record set is used. The unit cost of electricity is a variable within the database set manually. The logic behind this method can be found at *Appendix J.11* in the form of pseudo code.

A.12 Calculate installation depth factor for each site

This method produces an installation depth factorisation file using the DTI water depth file and the installation depth factor table in the database for each valid site and device.

To estimate an installation cost, which are figures that are not widely known, a table was set up in the database using a factoring system that assumes the deeper the site the

more expensive it is to install the device. Therefore, for each location the water depth is compared against the depth in the factor table, and the resulting factor value is then sorted in a output file in the usual fashion. The logic behind this method can be found at *Appendix J.12* in the form of pseudo code.

A.13 Calculate installation distance factor for each site

The logic behind this method is identical to that of *A.12*. Within the database there is a table for the distance factor which is this time used with the distance to power output file produced at *A.5*. A separate output file from this method is written in the usual fashion. The logic behind this method can be found at *Appendix J.13* in the form of pseudo code.

A.14 Calculate overall installation and decommissioning costs

This method uses several files and datasets to calculate a final maximum and minimum installation and decommissioning cost values for each valid site, and each valid device.

This method uses the output files produced at: *A.8 Calculate the number of devices required and device output at a given site*, *A.13 Calculate installation distance factor for each site*, and *A.12 Calculate installation depth factor for each site*. The method also uses the device, mooring method factors, and model values from the database.

The installation cost are determined by number of devices per cable, daily installation cost of device, number of days to deploy determined by the mooring method, and the depth and distance factors. The decommissioning cost is a percentage of the estimated installation costs.

The mooring factor values are stored as number of days and the mooring method assumes there will be an average number of days taken for a single device to be deployed. Each device has a different mooring method and it is also assumed that each method, on average, will take a differing length of time to deploy, which gives us our mooring method factor per device.

This method produces an installation cost and decommissioning output file in the usual fashion. The logic behind this method can be found at *Appendix J.14* in the form of pseudo code.

A.15 Add installation costs to device and cable costs

This method produces a total deployment cost from the device, cable and installation costs for each valid site and device. This is calculated from the device and cable cost, and installation cost files produced at *A.10* and *A.14* respectively.

The two previously produced output files are used by this method as input files, their values are added together and are written as a file containing the cost for both the device/cable and the installation cost at each location in the usual fashion. The logic behind this method can be found at *Appendix J.15* in the form of pseudo code.

A.16 Determine profit/loss for each valid device at each valid site

This method concludes the batch processes by determining a profit or loss figure in an output file by subtracting the overall costs from the revenue generated. The overall costs and revenue generated files were produced at *A.15* and *A.11* respectively. The value is written to file as a positive or negative pound value (or score indication) in the usual fashion. The logic behind this method can be found at *Appendix J.16* in the form of pseudo code.

A.17 Calculate distance between two given points

The Calculate distance method is one of the many sub methods (or scripts) used within the program to undertake a specific task and that can be used by various other methods within the program.

This method takes the distance from two points and refines the actual true distance involved with the correction formula, i.e. essentially the distance between the two points is accepted by the method which then calculates the correction required when considering spherical geometry. Once this has been achieved the method then returns the corrected distance value to the calling method.

The actual four input values passed to the calling method are: latitude distance, longitude distance, holding degree value (average latitude degree value from the two distances), and latitude seconds. The equatorial radius and pi values are stored within the method and various calculation variables are also set which will be described below.

Firstly, the input latitude and longitude distances are converted into nautical miles. The average latitude is then calculated in radians which in turn is used in a cosine calculation with the equatorial radius to produce a radius latitude variable. This variable is then multiplied by $2 \times \pi$ to produce the circumference latitude variable which is then divided by 360 to give the distance per degree longitude, and then converted into nautical miles. A longitude correction is then obtained by the longitude distance divided by 360 and multiplied by the distance per degree longitude. The overall result is finally gained by obtaining the square root of latitude distance nautical, plus longitude correction squared.

Therefore the point to point distance was calculated as the straight line planar trigonometric distance. The method then returns the overall distance to the method in which made the call. This method is called from: *A.5 Constructing a Distance Matrix from each site to closest power station*, *A.6 Construct a distance matrix from each site to closest port* in the batch process, as well as: *B.3 Find closest landing point* and *B.4 Find closest port* from the user process.

This method in the as built model has a fundamental limitation, in that the method assumes the distance is a straight point to point and does not take in to consideration cable and shipping routes which are not direct. Therefore the distance calculation may result in an underestimate of the true distance as the line may well go across headlands on the land mass as well as the sea.

The accuracy of this function could also be further increased if the earth was treated as an ellipsoid rather than a sphere. However, it was deemed for this project that this level of detail was not required as the increase in accuracy will not have a marked difference on the overall results, considering the various coarse resolution and assumptions used throughout the model. The logic behind this method can be found at *Appendix J.17* in the form of pseudo code.

A.18 Record dataset range values

This method is used to validate the largest and longest values within any dataset. This is important as the data structures within the model have a field set length which is a requirement when using random access files. If the field within the data structure is set too low then data will be truncated and therefore lost. If the field is set too high then file and memory space can be wasted. The method helped set data structures handling random access files. This was not done dynamically in the strictest sense, although the structure and methods are in place for a future revision to include this functionality. This method can also point out any potential anomalies within the dataset.

A.19 Output dataset range values

This method works with the record dataset maximum values by taking these values recorded and saving them to the dynamic external properties dataset within the database. The resulting record set can then be used to check that each data structure within the program has the right memory allocation. The record set will contain an entry for every output file with a largest and smallest value along with the corresponding filename.

A.20 Clear output dataset range

This method is used to clear the dataset range value record set, before each method's range values are stored, i.e. a new record set is created (overwritten) for every program run. This is required as a record of previous program runs is not required, and if any of the data change (i.e. the number of valid devices considering a file entry is made for every output file which is obviously different if a varying number of valid devices are found) then a fresh analysis of the dataset is required.

It is also important to remember if a new device (or information is obtained about a current device) then it is likely a new set of values will be run through the model that will produce different results. These results may exceed the allocation of the relevant data structures within the model and therefore highlights the importance of these storage, writing and resetting methods.

A.21 Write valid results dataset

This method is called from the *A.16 Determine profit/loss for each valid device at each valid site* method each time a valid result is identified. When a valid result is found, the current value, the location (in latitude and longitude seconds) and the filename is passed to this method where they are saved to the valid results dataset of the database. This dataset table is used in further operations to power the display functions of the program.

A.22 Clear valid results dataset

This method is used to clear the valid results record set before each new set of valid results are considered, i.e. a new record set is created (overwritten) every program run. A record of previous program runs is not required and if any of the data change then a fresh analysis of the dataset is performed.

A.23 Calculate cable cost without device validation

This method is a stand alone feature within the batch operation that no longer is part of the main batch operation run. This is for historical reasons as it was superseded during the development of *A.7 Calculate Cable Costs for each site against valid location for each device*.

This method is not device dependant, i.e. it checks each site and only compares the cable constraints, there is no cross reference validation with a device. Therefore, the data produced by this method can be used later in model calculations as long as it remembered that the device validation must take place.

The method has been superseded as it was deemed after it was written that a check as to where the device can go before checking the cable attributes was required, i.e. the cable cost can only calculated after a device fits a site, and if the cable attributes then match. This method on the other hand does not take the device location into consideration and prints a cable cost for a site if the site passes the cable attributes. The method also prints to file the minimum and maximum power output for a site.

This method has been left as a stand alone method within the model and can be run individually from the batch menu within the GUI. The results from this method are obviously different and for a spatial stand alone cable cost dataset it is actually a valuable test, as sites are not ruled out due to device restrictions.

It also shows that the methods within the model can be added/amended and still have an overall use, i.e. this small section of code has been superseded by another small method and both are still usable within the system without causing conflict. This method was by passed in the batch flow operation by altering the “call” handler which was one line of code which can be reverted.

APPENDIX B ALGORITHMS AND CALCULATIONS REQUIRED FOR MODEL USER OPERATION

The user operation mode employs much of the same logic that is used within the batch operation mode. What is different, is the order and location from which the logic is used. The batch operation works from the first line of code to the last, the user operation on the other hand works at stages at a time, depending on the users choice, which is captured as “events”.

Unlike the batch process, where each stored location site is processed one after the other until the end, the user operation takes a user entered location and therefore has to find that location within the random access file, a format that is excellent at allowing this. For this to work, the user’s desired site location (longitude and latitude) is captured and the location converted into a row and column location which is then used to call the relevant data within the various files and datasets.

There is also slightly more functionality within the user operation in order to allow the user to see (and therefore understand) what restrictions the system uses to pass data, i.e. they can alter key parameters at run time to allow a test to pass that would not normally within the batch operation. This extra functionality, and by the fact much of the logic is called from varying locations, means separate methods contain what is essentially the same logic required for the user operation.

B.1 Find GEBCO depth

This method is responsible for loading the GEBGO bathymetry data into the characteristics of site form.

The way in which the method does this is to take the users entered location and compares this to the north west boundary of the dataset which is stored locally within the method. A calculation is then used to determine the “difference” in the locations which is then converted into a column and record number (location) that is used to directly determine the location within the GEBCO file.

The entire record that contains the single value corresponding to the location the user entered, is loaded into a locally declared data structure. Using this data structure, the relevant column is located and the value displayed onto the characteristics of site form.

B.2 Find DTI resolution data

This method works in a very similar fashion to that of *B.1 Find GEBCO depth*, and is used to load the various DTI datasets for display. The only reason the two methods had to be handled differently was because the GEBCO data are in a different resolution to the rest of the data used within the model, i.e. the GEBCO dataset was the first dataset to be trialled within the project and it was not until the DTI data were obtained that the actual boundary of the project was defined. The GEBCO data were left at the original resolution as the model is versatile enough to read only data required. However, a separate method was used for the GEBGO data in this instance to keep the program structure neat and easy to understand.

Therefore, this method is responsible for loading all the data (other than the GEBGO bathymetry data) into the characteristics of site form.

The way in which the method does this is to declare a local results array to the size of 28 which represents the number of data files the method has to handle. The details of the file location, field character size (variable length) is held within the external random access files record set within the database so this is read from beginning to end.

When reading the external random access files, each record has the field character size checked (which is vitally important for the random access file format) and once this is found a data structure for the record that is to be read can be set up to accept the data.

Once the data structure is in place, the file can be opened and the relevant record read into the local data structure, and in turn the relevant column (data field) is then read into the local results array. The method will then continue this process until every one of the 28 random access files have been processed, and values captured within the local results array.

The method prints out the contents of the local results array, which is a string array containing 28 values. The “Characteristics of site” form has a corresponding 28 labels in place to accept the data and they are labelled with the corresponding data description, e.g. “DTI Water Depth”. The “Characteristics of site” form with the 28 array values is shown at *Figure 4.2*.

The method also carries out a couple of smaller tasks such as converting the DTI distance to shore value from metres to kilometres and nautical miles and printing the results. The closest landing point and port are stored within the file as ID numbers, so the relevant power station and port record sets have to be searched within the database in order to load the actual names of these sites. The distance of these sites are also displayed in kilometres.

B.3 Find closest landing point

This method was one of the first methods written and was used initially as part of a smaller trial cable/distance model. When the DTI data were obtained the method was largely superseded by: *A.5 Constructing a distance matrix from each site to closest power station*, and *A.6 Construct a distance matrix from each site to closest port*

This original “point to point” method takes the user entered location and calculates the direct point to point distance to the each power station within the database, and the result is the closest power station/landing point. This method will also return a valid value regardless of the user’s selected location being on land or sea.

The alternate method that superseded this method, uses the previously documented two output files produced by the batch operation of the model. This places a distance in the distance file and the power station/landing point ID in the other. These files are structured within the model resolution of 1 minute from north to south and 0.666 minute from west to east and have an internal structure that allocates a data value sector at each increment from north to south and west to east. The result values in the file represents the distance to the closest power station from the static location within the file.

Incidentally, the method used to calculate the distances within the file, is the same as used within the point to point method, just the starting values of the site is different, i.e. from the file the increment static point is used as the start point, where the point to point

method uses the exact location. Therefore, the results will differ due to the fact the file location increments uses the closest location result at the resolution available, as opposed to using the exact locations.

Therefore, the point to point result is slightly more accurate as it is taking the actual point to point values of the two locations in question. The results from the point to point are shown as a reference, as the result in the file is actually used within the model for all further calculations.

The way in which this method actually undertakes the point to point task is to run through the entire power station record set from the database, and for every entry in the set the distance from this entry to the users entered location is calculated. This is done using the latitude and longitude of the power station entry, the users entered location in latitude and longitude which is passed to the method *A.17 Calculate distance between two given points*. *A.17* will then return an overall distance result to this the calling method.

As the power station record set is processed, the local method variables that hold the name and distance of the closest power station are overwritten, if the current power station location is closer. Once the entire record set has been processed then the name and distance of the closest power station is be printed to the characteristics of site form screen. There is also a logical test to ensure each power station has enough spare capacity to allow a new connection. This is achieved by comparing the overall distance of the site with the corresponding cable length. The cable type can then be determined with its corresponding rating, which can be compared with the power station spare capacity.

It was seen to be beneficial to leave this original method for the distance calculation, as it acts a way to ground truth the results and also shows the versatility of the model where more than one method can be used without interfering with one and other.

B.4 Find closest port

This method is very similar to the *B.3 Find closest landing point* method in that it broadly shares the same structure and logic. The main difference is that the method is

using the port record set within the database in order to find a result rather than the power station record set. The port calculation logic also does not validate any spare capacity as with the power station calculations.

B.5 Calculate distance between two given points

The Calculate distance method is one of the many sub methods (or scripts) used within the program to undertake a specific task and that can be used by various other calling methods within the program. The method is used by both the batch and user operations of the model and for that reason has already been described at *A.17 Calculate distance between two given points*.

B.6 Select a device

This method is called from the characteristics of site screen at the point where the user selects the criteria in order to find a device. The results of this method are shown on the device results screen.

The method determines the criteria the user has entered, such as to find the device results corresponding to: depth, distance from land, resource, and the resource range they have selected, if any.

The method achieves this by a series of logical operations. The method first checks if the user has selected results for depth. If the user has selected depth then the method then checks, for each device in the device record set, the depth at the site location is within the bounds (or equal) to the operational depth of the device. If so, then the device ID is written to the device holding table record set. A list box for devices within depth range on device results screen is also populated by each device that passes this test.

The method then carries on with a similar operation with the resource calculation. The method first checks if the user has selected results for resource. If the user has selected resource, the method checks for each device in the device record set, the resource at the site location is within range to the operational resource of the device. If so, then the device ID is written to the device holding table record set.

In order to do this, the logic in this section is slightly more complicated than for depth described above, as in the device record set we only know the ideal resource for each device, so a percentage is used estimate what the maximum and minimum would be from the ideal figure. The percentage is a user defined item within a combo box with the data range from: “10%” to “100%” or “Seasonal & cycle extremes”.

The way the method works out the maximum and minimum range values for both wave and tidal devices is by assigning local variables and adding and subtracting the users selected percentage to the site’s relevant power values (annual mean wave power or mean spring peak flow) to give the variables: maximum wave resource, minimum wave resource, maximum tidal resource, and minimum tidal resource. If seasonal & cycle extremes is selected, the method assigns the range values with the relevant power values at the site: winter/summer mean wave power or mean spring/neap peak flow.

Once the device maximum and minimum resource ranges have been defined at the site, the device’s ideal operational power figure can be directly tested to see if it is within the ranges defined, and if so, as mentioned above, the device ID will be written to the device holding table record set. A list box for devices within the resource range on the device results screen is also populated by each device that passes this test.

As a matter of interest and as a recap: the batch operation calculation checks if a wave device ideal operational power figure is greater or equal to summer resource and less or equal to winter resource, i.e. if the device figure is within the seasonal extremes. For a tidal device the batch method checks if the device operational power figure is greater or equal to the neap resource and less or equal to spring resource, i.e. cycle extremes. Therefore, the user option of “Seasonal & cycle extremes” is the method used by the batch operation.

The “Seasonal & cycle extremes” compared against the annual power ranges, will work out to be within the middle range of scale provided by the model, i.e. the user can exceed the seasonal values with the percentage range provided by the model.

Therefore, the resource within the user method can be reduced or raised which will affect the number of valid devices found. Below is an example for the random selected location: 59°, 59’ north and 3° 3’ west, to show the relationship and scale between the two different systems used by the user method:

Annual mean wave power 34.37 kW/m

Summer mean wave power 11.47 kW/m (~33% of annual mean wave power)

Winter mean wave power 57.26 kW/m (~60% in excess of annual mean wave power)

Mean spring peak flow 0.61 ms⁻¹

Mean neap peak flow 0.3 ms⁻¹ (~49% of mean spring peak flow)

It is worth noting at this point the model deals with the wave and tidal devices differently. The wave device's operational resource can be compared to the annual mean wave power (a figure expressed in kW/m) with the option of adding various percentages to this, i.e. the annual figure roughly sits between the Summer and Winter extremes and in a sense acts as an average between the extremes. By allowing this adjustment the user can vary the calculation used by the model.

For tidal devices the logic is slightly different in that an annual figure is not used in the user method. An annual mean tidal power (expressed in kW/m²) does exist, however it was felt that to use the mean spring peak flow as the start point for the users alteration of the device resource test was adequate, considering the user method is more a display option in comparison to the batch method that uses the more accurate and strict range restrictions. The method used by the batch method can also be selected by the use of the range extremes in any case. With the use of only the mean spring and neap peak flow values, avoidance of the differing formats of kW/m² and ms⁻¹ was achieved. Wave and tidal developers also use the differing formats with wave using the kW/m value to determine output and survivability, with tidal developers using the tidal velocity. The output figures are gained by the relationship between the tidal velocity, and the output from the device at this velocity.

The method proceeds to check that the distance to land figure is within range of the devices range limit. The logic behind this is similar to that of the depth operation with no specific test for wave or tidal devices. Devices that do fall within the range have their device ID is written to the device holding table record set in the usual fashion. A list box for devices within distance range on the device results screen is also populated by each device that passes this test.

The method also carries out a couple of smaller tasks such managing the holding table record set so that no old results are held from previous workings. All result containers

(list boxes and so on) in the device results screen also have to be cleared on each method run for the same reason, i.e. results from previous working are deleted from the record sets so that they do not interfere with the any current workings.

B.7 Display union device results

This method follows the work started by *B.6 Select a device* to determine how many devices pass each test, and displays the results in the device results screen. The way in which this is done is a little cryptic. By using the device holding table record set, the method is able to determine how many times each device appears in the device holding table record set, and test if this value matches the number of criteria the user entered. In other words, if the user has selected all three criteria on the sites characteristics screen then the device has to appear three times in the device holding table record set, otherwise it did not pass all three tests and is therefore not considered a valid device. This also applies if the user has selected one and/or two of the criteria, i.e. each device within the criteria(s) have to appear in the holding table record set a given time to pass the test.

If the device does appear in the device holding table the same number of times as the user requested, then the device name is written to a combo box that is further used in user selection. Therefore, the logic behind finding the device union, that matches one to three (depth, resource, distance to land) of the users selection, can instantly be tested by using the combo box, i.e. the combo box will only contain devices that will appear in each of the three result list boxes for each of the criteria: depth, resource, and distance to land within the device results screen.

This method (like many within the model) was originally part of a larger method (*B.6 Select a device*) which was carrying out many different tasks. Therefore the decision was taken to construct a new method to carry out this specific task. This has several advantages, mainly it breaks the code into more manageable sections and is therefore easier to read. It also creates the advantage that the specific logic within the method can be called at any time within the model if required, without having to run unnecessary lines of code.

B.8 Calculate site output

This small method is used to run through the device record set once the user's selection from the device results screen is matched to the relevant entry within the device record set. The devices output is then used with the number of devices the user has entered within the device results screen. The result of this calculation is printed to the cable and costing results screen as the "Site output"

B.9 Calculate cable details

This method works out a feasible cable type for a particular site and device, and if a feasible cable type is not possible the user is told why. The device in question is of course a valid device the user has selected in the device results screen. In the device results screen the user can only select a device that passes the depth, resource, and distance from land test, in which the user can alter the scale of the test as described at *B.6 Select a Device* and *B.7 Display Union Device Results*.

The method achieves its aim by using the cable record set. Within this record set there are three forms of cable technology that were identified through a study of electrical cabling used (and planned) for the offshore wind industry. These 3 cable types have a very different criteria in the form of cable distance, and cable power rating (site output). The logic works with the distance criteria first, checking that the site to landing point distance is within the cable minimum and maximum values.

If a valid cable type is found for distance (and it will be one as the distance values do not overlap with the input data supplied) the logic will continue to test the site output with the cable criteria, i.e. the logic assumes that the distance is the critical factor and that if the distance is not within range then the test will not continue. An overlap option for cabling is an option that could be provided in a future revision of the model with different input data.

The power rating of the cable is then compared to the site output, which is stored on the cable and costing results screen and was calculated by the *B 8 Calculate site output* method. If the site output is within the cable maximum and minimum power range then the valid cable type is printed to the cable and costing results screen. A cost is

calculated from the distance to the landing point from the site, and the cost per distance stored within the cable record set.

If the output of the site is not within range then the logic tests to find out if the output is either short or in excess of the particular cable's power range, displaying on the cable and costing results screen the result, in the form of a device short or over fall figure in relation to the cables maximum/minimum power range, site output, and the individual device output, i.e. the site output is controlled by the number of devices and their individual output. Therefore the site output short or over fall in MW is compared to a device's individual output and the number of devices can then be determined as to a number short or over the required amount in order to fall within the cable power range. The logic behind this is for example: Short/Over Fall = (Site output – Max/Min Cable output) / (Site output /Number of devices). Where the number of devices is a user entered value, after they selected a valid device at the device results screen.

There can be the situation where the distance may be out of range. The three cable types have different distance ranges and do not overlap. The 33kV cable starts within the database with a minimum distance of 0 km and the HVDC type has a maximum distance of 500 km. In essence there cannot be a distance over or short fall considering the number of landing points within the boundary, and that distance from 0 can logically be catered for. However the logic has to exist to cater for the eventuality that the cable details and available landing points may change. Therefore if the logic finds that the site distance to the closest landing point is not within the cable range, the distance short or over fall is displayed within the cable and costing results screen.

A boolean check marker is used within the logic and if a valid cable type is found the method proceeds to call the seven remaining user methods required to find an overall profit/loss result which is displayed within the cable and costing results screen, i.e. once the cable and costing results screen has been reached by the program no other user intervention is required and therefore this screen is the last "calculation" screen. Therefore, all results for this method are displayed on the cable and costing results screen.

B.10 Calculate overall device cost

This is the method that is used to insert onto the cable and costing results screen the overall device cost for number of devices chosen. This is done by comparing the users selected valid device on the device results screen, and running through the device record set to find out the individual cost of the selected device. Once this cost is known it can be used with the number of devices the user has selected on the device results screen to calculate an overall cost.

B.11 Calculate installation depth factor

This method calculates an installation depth factor for the site. The model assumes that the deeper a site then the more it will cost to install a device. The increase in cost with depth is unknown so an installation depth factor record set has been set up containing a large sequential range of depths that have a factor assigned to them, so a simple extra cost per depth can be calculated. The scale used within the record set can then be modified by the user in the database when more knowledge on the cost per depth is known. At present a simple score is used per water depth to show the working of the structure: 0 to 25 metres scores 1, 26 to 30 metres scores 1.1 31 to 35 metres scores 1.2 and so on up to 260 metres that scores 4.8.

The way in which the method carries out his task is to take the DTI water depth stored on the site characteristics screen and compares it to the range of depths stored within the installation depth factor record set. Once the depth range is found (the range goes in 5 m increments) the factor is read and printed to the cable and costing results screen.

B.12 Calculate installation distance factor

This method calculates an installation distance factor for the site. The model assumes that the further away a site then the more it will cost to install a device. The increase in cost with distance is unknown so an installation distance factor record set has been set up containing a large sequential range of distances that have a factor assigned to them, so an extra cost per distance can be calculated. The scale used within the record set can then be modified by the user in the database when more knowledge on the cost per depth is known.

The logic behind this method is identical to that of *B.11 Calculate installation depth factor*, with the only obvious difference being the distance to the closest port is used with a separate installation distance factor record set within the database.

Once the distance range is found (the range goes in 5 nautical mile increments) the factor is read and printed to the cable and costing results screen.

B.13 Calculate user installation costs

This method adds an installation cost from the mooring type of the device and the number of days associated with installing that mooring type. The method achieves this by using the mooring method factor record set which has a factor for each device mooring type. The method also has to use the device record set and once the user's selected device is found the mooring type within the device record set is then compared to the mooring type within the mooring method factor record set in the database.

Once a match is made the daily installation cost from within the device record set is multiplied with the number of devices the user selected (stored within the device results screen), the number of days value from the mooring method factor record set, the installation depth factor and installation distance factor (which are both stored on the cable and costing results screen) to give the final installation cost that is also displayed on the cable and costing results screen.

B.14 Calculate decommissioning cost

This method provides a decommissioning cost estimate for the site. The method achieves this by using the model values record set which has an assigned decommissioning cost percentage that is used with the installation cost value which is stored within the cable and cost results screen. The model assumes the decommissioning cost will be a percentage of the installation cost and the percentage can be set in the main database. The result of the method is displayed on the cable and costing results screen.

B.15 Calculate revenue

This method provides a revenue stream value for the site. The method achieves this by using the model values record set which has an assigned unit price for electricity that is used with the site output value (which is stored within the cable and cost results screen) and the design life of the device. The design life of the device is also checked, and if does not exist the default design life assigned is retrieved from the model values record set. The result of the method is displayed on the cable and costing results screen.

B.16 Calculate total profit/loss

This method concludes the user operation of the model. The total costs value is calculated from the: cost of cable, total number of device cost, installation cost, and decommissioning costs which are all stored within the cable and costing results screen as a result of the corresponding methods described above. A profit/loss score value is then obtained by using the revenue generated value minus the total costs value which are again within the cable and costing results screen. In the usual fashion the end result is displayed on the cable and costing results screen. As part of the built model, discounting and Internal Rate of Return (IRR) is not considered, however, the model can easily be extended to include these in the financial calculations.

APPENDIX C GLOBAL ALGORITHMS AND CALCULATIONS REQUIRED FOR GLOBAL OPERATIONS

Although there are two distinct modes of operation provided by the model (user and batch) there are several methods that are required and used by both. The code has been structured in such a fashion so the following methods can be accessed from either mode.

C.1 Set global variables

This method defines the main database and working directory, i.e. where database and various data files are held. This eliminates having to use the same line of code in each procedure that calls the database

The working directory of the database and files is stored in the database itself and has to be changed within the database record if the system is used at a different location. The method is equally important for both the user and batch operations of the application.

C.2 Calculate device parameters

In addition to the batch methods within the program there are also various methods that support the main processes described above. The calculate device parameters method is a method that is called when the program is loaded. The purpose of this method is to populate device parameters within the database with other run time data parameters.

One of the main functions is to calculate the overall cost of a device. For this, the method uses the material that the device is constructed from (base material) and the overall tonnage of the device. If the device is constructed from more than one material then the percentage of the materials is taken into consideration. The tonnage and base material(s) of the device has to be known (and the method validates that this is the case), which is used with the material cost record set within the database.

This method as part of the device cost, also works out the Power Take Off (PTO) costs for the device, i.e. the PTO costs are added together in order to get the total device cost. The PTO costs are calculated with the PTO record set within the database holding an

assumed value (although this is changeable in the usual fashion) for each PTO system in terms of rated kW per device output. As with base materials, the device may have several combined PTO systems in order to convert energy, and these are added to the overall PTO and device cost.

The method also calculates the power to weight ratio of the devices which is stored within the database for future reference.

C.3 Calculate power station and port minutes

This is another method that is called as soon as the program is loaded. The method allows for the correct location conversion to be undertaken for newly entered power station/port in their relevant record sets. That is, the method will calculate the longitude and latitude seconds from the users entered longitude and latitude degrees, minutes, and seconds. The method does this by checking that each entry has a valid longitude and latitude value entered either by user, or previously by this method and if not, the relevant second value is added. All locational calculations executed in the model are undertaken using seconds only, as it is easier to compare location values, as well as incrementing/decrementing locational values and other such calculations. This convention is however only used in the background of the model, as all location values are displayed to the user in degrees, minutes and seconds. The user may not know what the second value is when they make a new entry so this method does it for them.

APPENDIX D ALGORITHMS AND CALCULATIONS REQUIRED FOR RANDOM ACCESS TEST FACILITY

When the model was under construction a random access test facility was developed in order to help test the various random access files, and therefore the model as a whole. The facility has been built into the application as it still provides a useful function in its own right and will also be beneficial as future data are added.

D.1 Setup display combo for test function

This method runs through the external random access files record set (which is a set containing information about the random access files the model uses) and appends the file paths into a combo box within the testing form screen. This is so the user can select a file path to view various results rather than having to type the path out.

This method also runs through the device record set and enters all valid devices into a list box within the same testing form. The user has to use this in conjunction with the combo box as the combo only displays each type of random access file, rather than every single random access file, i.e. not each file type with each valid device is displayed in the combo box, only the essential random access file structure as it were. The device number has to be entered by the user and hence the reason for a display showing which devices are available for that file type. Its use during testing is discussed fully within *4.5.2 Batch operation example walk through*.

D.2 Random access file test facility display

This method allows the user to enter record and row locations in order to find out its value within a random access file. The method is called from a windows event embedded within a command button on the test result form.

The method initially finds the users selected file and calls up: the data field character length (the field length, required in random access files), the value's unit, and the resolution (rows and columns used) which are all displayed on the testing form screen.

The method then reads in the desired record from the data file into a data structure with a length defined by the data field character. The record and subsequent user desired field within the record is selected using the values entered by the user in two input boxes in the testing form screen. The method also validates that the user's entry is within the boundary of the datasets row and columns.

The method also keeps an internal count of the location so that when the user enters a record and field location the actual location in latitude and longitude can be displayed on the testing form screen. The user operation of the test facility and form is described in *4.5.2 Batch operation example walk through*.

D.3 Calculate random access data file statistics

This method allows the various data file statistics to be displayed on the testing form screen. To carry out this task there are actually seven methods that are all similar in operation. These methods run through the current data structure that is in use by the random access file test facility method. With the testing facility, the user has the choice to call up any of the random access files all of which are different sizes. For example if the user selects the mean water depth from tidal dataset the data field characters (variable length) are set at 4 characters (digits) each. If the user selects the distance to land data then the character size (variable length) is 6. Overall there are seven different data structures with seven different variable lengths set: 2, 3, 4, 5, 6, 9 and 13. The smallest (2) is for boolean sets that contain either 0, 1, na, or NA, and the largest (13) is required for large costing values and is the variable length for most of the costing data structures such as the final profit/loss results.

Therefore, depending on which file the user has selected, the corresponding statistical report method will be called that matches the data structure size required to hold the data from the users selected file.

The reason for this effort is to allow the testing facility function to show the overall statistics of the dataset the user has selected. The results returned are: NA count (sites where no data existed for, such as a location on land), na count (a site where data does exist but for whatever reason the site did not produce a valid result for this particular

site against device), valid count (where a valid value exists within the dataset for the site) and a total of all values, which will match the overall field count of the dataset. This method (and the 6 other logically identical methods) allow a relevant sized data structure to be populated with the data within the file selected by the user. The way in which the method does this is to read a record at a time into an internal method data structure set to the size of one data file record. For these imported records, the various statistical counters required are incremented until the end of the record is reached. The method then overwrites the internal structure with the next record of the data file (i.e. for each record row by row from the beginning, the method increments the various internal method counters depending on each data field's value, until the last data field in the last record row has been reached).

APPENDIX E ALGORITHMS AND CALCULATIONS USED FOR DISPLAY RESULTS FACILITY

As part of the batch operation there is an extension to the functionality with a facility to display the results from any of the final batch output files, i.e the overall profit/loss results. The way this works is that valid results within any of batch profit/loss output files can be searched and loaded in a display for the user. The logic required to do this is described below.

E.1 Display overall profit/loss statistics

This method is called from two different forms, one is the random access testing form of which the main operations are described above (*Appendix D algorithms and calculations required for random access test facility*), and the display results facility which is described within this section.

The main function of the method is to provide the random access test facility and the display results facility a statistical overview of the results of the profit/loss random access result files.

The results that are printed on the screen forms of the random access test facility and the display results facility show all profit/loss result statistics, that is, every profit/loss result for every device and cable that had an output file created.

The results returned are: NA count (site where no data existed for, such as a location on land), na count (a site where data does exist but for whatever reason did not produce a valid result for this particular site), valid count (where a valid value exists within the dataset for the site) and a total count for all the values. The number of profit/loss files is also displayed with the number of data entries per file. For the current model set up (with the defined project boundaries, and therefore corresponding size and structure of the data files) the entries per file will read 234000 (450 rows by 520 columns).

The way in which the method does this is to take each device at a time, while looping through the device record set, to find a file within the profit/loss file directory that matches that of a current device name. When the profit/loss file for that device (that is,

each cable type associated with the device) is found it is loaded into an array of data structures one record at a time. The array contains a data structure for each profit/loss result, i.e. the device with each cable type. The individual data structure is the size of one record of the data file so each record line (row) of the data file is read into the data structure at a time. As each record, and then each data field (column within the record row) is read a counter is incremented depending on the field's value. The value will either be: "NA", "na", or a real number.

Once the counters for all the data fields in all the records of all the files, for each device have been incremented, the results are displayed on the form that called the method, i.e. either the random access testing facility or the display results facility.

E.2 Load files with valid results

This method loads a list of valid profit/loss filenames within a combo box in the display results form, i.e. the main task of the method is to search through the valid result record set and load every unique filename into the display results form file combo box situated for the user to select one of the valid filenames.

The method uses the valid results record set within the database which is created by the *A.21 Write valid results dataset* method, which is called within the *A.16 Determine profit/loss for each valid device at each valid site*.

The valid results record set holds an entry for every valid result identified within the entire profit/loss files. Every unique filename that is identified within the valid results record set is copied into a new holding record set which is then sorted in ascending order by a database query and again saved as a new holding record set. These holding record sets are a convenient way to manipulate the datasets without having to do anything more than copy data from the original tables.

These sorted results are then loaded into the combo box. Within this method there is also the requirement to manage these two "holding" record sets so that no old results are still held when this method is run.

E.3 Display results

This method populates the list box within the display results facility with the profit/loss results relevant to the user choice in the file selection drop down combo box.

The method does this by comparing the users selection (filename from combo box) with the filename field of every record in the valid results record set within the database.

When a match on the filename is found then the record from the valid results record set is written to a holding table which is another temporary record set used specifically for transferring the relevant data for the display results facility. Within the user combo box there is also the option to select all results, and in this case all the profit/loss results are used to populate the display list box.

The method then checks and records the user radio box choice which will determine the order in which the data are displayed. Each option has a corresponding index which is recorded and passed the *E.4 Sort results* method.

Within this method there is also the requirement to manage the holding record set so that no old results are held when this method is run. The list box also has to be cleared before any new and/or sorted data are entered.

E.4 Sort results

This method takes the user option to order the resulting data (latitude ascending/descending, longitude ascending/descending, value ascending/descending) and updates the display results form display list box with the results.

The way in which the method does this is to take the holding record set created at *E.3 Display results* (which contains all the data required, just maybe not in the desired order) and from within the method a relevant database query is run to append the data in the desired order to a new record set called sorted results.

The method has to check the user choice and this is done with the radio box group identifying index which has been passed by the *E.3 Display results* method. A database query exists for each possible index value and once the relevant query has been

executed the sorted results record set will list the data in the desired order. The method then populates the list box with the data from the sorted results record set.

Within this method there is also the requirement to manage the sorted results record set so no old results are held when this method is run. The list box also has to be cleared before any new and/or sorted data are entered.

APPENDIX F OTHER WINDOWS RELATED METHODS AND FUNCTIONS

There are other methods within the program to handle various windows events, code sequence, and data loading functions. These methods do not necessarily provide any input to the calculations, rather they carry out window tasks for the overall application. Most are carrying out small tasks with as little as one line of code. Some are however more substantial and the most important methods are described below.

F.1 Enter location of deployment site screen, Form_Load

This is the first method executed in the application for the initial display screen. Behind the screen a From_Load event has a method to call three methods (*C.1 Set global variables*, *C.2 Calculate device parameters*, and *C.3 Calculate power station and port minutes*) which are all involved with setting various database and global variables required by the application.

Since all combo boxes within Visual Basic have to be populated at run time the method also populates the six location combo boxes with relevant data given the boundary of the project area.

F.2 Enter location of deployment site screen, location combo box events

On the opening data entry screen (Enter location of deployment site) there are six combo boxes that contain the various options for the user to enter their desired location. The data selection in the combo boxes is what the model will use as its location. This is the reason combo boxes are used, as unlike text entry boxes, combo boxes give much greater control, however a level of validation is still required. This mainly happens for example when the highest or lowest degree value is selected, then depending on the boundary, the number of minutes and seconds will not be the full 60 range.

Both the degree and minute combo boxes for both longitude and latitude have events associated with them that allows the program to drop down into the logic required to ensure the data values within the combo boxes is consistent with the project boundaries, i.e. the user is able to select any site location within the boundary, but not a location out with the boundary. All combo boxes have to be populated at run time, and since the

user has the option to change these values, the combo boxes must have the ability to update with the changed values at run time.

For the four methods required to do this, the logic is mainly the same. To give a brief description of each:

Latitude degree combo box ensures when the latitude degree combo box has a user selection of “61” the latitude minute combo box is populated with a data range from “0” to “29”. The way in which the method does this is to identify the value entered into the latitude degree combo box and a loop (set to terminate depending on the degree value entered) will populate the latitude minute combo box on the loop’s increment index.

Longitude degree combo box ensures when the longitude degree combo box has a user selection of “-9” the longitude minute combo box is populated with a data range from “0” to “35”. The method continues to ensure when the longitude degree combo box has a user selection of “3” the longitude minute combo box is populated with a data range from “0” to “23”. Otherwise the longitude minute combo box is populated with a data range from “0” to “59”. Due to the longitude boundaries involved, the method also has to look after the longitude seconds and when the longitude degree combo box has a user selection of “-9” or “3” the longitude second combo box is populated with a data range from “0” to “15”, otherwise the longitude second combo box is populated with a data range from “0” to “59”.

The logic behind this method is slightly more complex than the other combo box methods described in this section due to the fact this method has to control both the corresponding minute and seconds values. The way in which the method does this is to identify the value entered into the longitude degree combo box and two loops (set to terminate depending on the degree value entered) will populate the latitude minute and second combo box with the increment index of each loop.

Latitude minute combo box ensures that if the user has selected “61” in *latitude degree combo box* and the user has selected “29” in this the *latitude minute combo box* then the *latitude second combo box* is populated with a data range from “0” to “29”. Otherwise the *latitude second combo box* is populated with a data range from “0” to “59” with the same logic as described for *latitude degree combo box*.

Longitude minute combo box ensures that if the user has selected “-9” in *longitude degree combo box* and the user has selected “35” in this the *longitude minute combo box*, or, if the user has selected “3” in the *longitude degree combo box* and selected “23” in this the *longitude minute combo box* then the *latitude second combo box* is populated with a data range from “0” to “15”. Otherwise the *longitude second combo box* is populated with a data range from “0” to “59” with the same logic as described for *latitude degree combo box*.

F.3 Enter location of deployment site screen, enter location, command button

This method is linked to the “enter location” command button located on the initial enter location of deployment site screen. Therefore, when the button is clicked the model drops into this method and the code within it is executed.

This method takes the values that the user entered in the location combo boxes and converts these values into a single second values for the model to use. Since the boundary of the project spans both sides of Greenwich meridian, there are both western and eastern values from Greenwich meridian available to select. The general convention with latitude and longitude refers to coordinates west or east of Greenwich meridian, indicated by either “W” or “E”. The model uses this system with the slight change in that the system is completely numerical and uses positive and negative values to indicate western or eastern values which is common practice for numerical coordinate systems. Therefore, within the model -1° indicates 1° west of Greenwich meridian. When selecting from the enter location coordinates screen, the minute and seconds values are displayed as positive results such as -1° , $1'$, $1''$.

The method is responsible for converting all locations values to the same scale, and into a single location values in seconds. The method also performs other tasks such as displaying the chosen location within the site characteristics screen which is the next step in the user system. The values displayed on the site characteristics screen show part of the result of the conversion of the coordinate values, which is also used as a test facility, i.e. the values shown on the site characteristics screen are the values after they have been converted to the same positive or negative scale which will match what the user has selected. For example $-1^{\circ} 1' 1''$ will be displayed as $-1^{\circ} -1' -1''$.

The method also calls the initial user operation main model methods (*B.1 Find GEBCO depth, B.3 Find closest landing point, B.2 Find DTI resolution data, B.4 Find closest port*) which are described at the indicated index. The method also calls (*A.6 Construct a distance matrix from each site to closest port, and A.5 Construct a distance matrix from each site to closest power station*) methods in case the port/power record sets have changed since the last model run, i.e. these methods are within the batch operation, however they are responsible for constructing the data matrixes required by the user operation as well, and if this was not done (and if the batch operation was not run after a port/power record set update) then the new data within the record set(s) would not be considered by the model.

F.4 Characteristics of site screen “Find device”, command button

This method is linked to the find device command button on the characteristics of site screen and when the button is clicked the application drops to this method which is responsible for validating the user selection, and either takes the user to the next stage or reports a problem.

Since the boundary of the project is in the shape of a matrix, and the underlying data were converted to conform to this shape, there are areas around the perimeters where valid data are not available, set by the model to read as “NA”. Therefore, the method tests that the site the user has selected contains valid DTI: water depth, resource, and distance to land values. In this instance all the DTI data are matched to the same coverage, so if one data value exists, then all will exist. However, this may not be the case with future tests, as the logic will test for any of the three values to be valid in terms of comparison with the device, and will only let the user proceed if the criteria they selected contains a valid result, regardless of the other non selected criteria. If a valid value is not available for a user selected criteria (water depth, resource, distance to land) the logic will un-tick the check box used for that criteria. The method then checks that at least one check box is still ticked and if so the device results screen is loaded and the *B.6 Select a device* method is called. Otherwise the user is notified of the problem via a windows message box.

F.5 Device results screen, select device, command button

This method is contained within the click event of the “Select device” command button within the device results screen and is responsible for validating the users entry from the “Total available devices” combo box and the text box allocated to the “Number of devices for site” option for the user.

The method first checks that the “Total available devices” combo box has been populated with at least one device. The program logic populates the combo box if a device passes the criteria set by the user on the site characteristics site. If no entries exist in the combo box then the user is informed. If on the other hand a valid device does exist, the method then checks the user has made a selection from the combo box, informing them of any problem. If a device has been selected and the number of devices they require for a site has not been entered, then the user is informed. If a device has been selected with a valid number of devices entered then the logic continues and calls the *B.8 Calculate site output*, and *B.9 Calculate cable details* in sequence, and loads the cable and costing result screen, with the distance also loaded for the closest power station from the sector file result within the site characteristics screen.

F.6 Batch menu, run batch, command button

This method is contained within the click event of the “Run batch” command button within the batch menu screen and is an example of a method within the application that is simply in existence to run important methods in sequence. The method calls all the main batch process methods in order, and displays a windows message box when completed. The methods called are: *A.20 Clear output dataset range*, then every batch method from *A.1 Determining a spatial distribution for each device* determined by water depth to *A.16 Determine profit/loss for each valid device at each valid site*. The historical method *A.23 Calculate cable cost without device validation* is also called at the end for completeness.

F.7 Load entity record set data

On most of the screens around the application if the user is presented with a result (such as the closest port, or power station) or they have to make a choice (device or power

cable) then they are given the option to load the data held within the database on this entity. The logic behind all the entities is the same, and is achieved by the relevant record set being searched, and, once the relevant entity is found the method loads each data value into a corresponding data label (container) within the relevant screen. This method exists within the user operation for each of the following record sets: port, power station, device, cable, and developer company.

APPENDIX G, LIST OF DATASETS USED BY THE MODEL (AS BUILT)

G.1 DTI Datasets, *in form*: Name of dataset (unit)

- Distance to shore (Metres)
- Water depth (Metres)
- Mean spring tidal range (Metres)
- Mean neap tidal range (Metres)
- Mean spring peak flow rate (Meters per second, ms^{-1})
- Mean neap peak flow rate (Meters per second, ms^{-1})
- Annual mean tidal power (kilowatts per metre squared, kW/m^2)
- Mean spring tidal power density (kilowatts per metre squared, kW/m^2)
- Mean spring tidal power density (kilowatts per metre squared, kW/m^2)
- Annual mean significant wave height (Metres)
- Spring mean significant wave height (Metres)
- Summer mean significant wave height (Metres)
- Autumn mean significant wave height (Metres)
- Winter mean significant wave height (Metres)
- Annual mean wave power (kilowatts per metre, kW/m)
- Spring mean wave power (kilowatts per metre, kW/m)
- Summer mean wave power (kilowatts per metre, kW/m)
- Autumn mean wave power (kilowatts per metre, kW/m)
- Winter mean wave power (kilowatts per metre, kW/m)
- Annual mean wave period (Seconds)
- Spring mean wave period (Seconds)
- Summer mean wave period (Seconds)
- Autumn mean wave period (Seconds)
- Winter mean wave period (Seconds)

G.2 GEBCO Data

- Bathymetry (Metres)

G.3 Automated static model data

- Distance to power station (Nautical miles)
- Closest power station ID (ID)
- Distance to port (Nautical miles)
- Closest port ID (ID)
- Cable cost 33 kV (£)
- Cable cost 132 kV (£)
- Cable cost HVDC (£)

G.4 Automated model data, for any given device

- [Device ID x] Distribution by depth (Binary 0 or 1)
- [Device ID x] Distribution by distance (Binary 0 or 1)
- [Device ID x] Distribution by resource (Binary 0 or 1)
- [Device ID x] Union distribution by depth/distance/resource (Binary 0 or 1)
- [Device ID x] 33kV min device cost (£)
- [Device ID x] 33kV max device cost (£)
- [Device ID x] 132kV min device cost (£)
- [Device ID x] 132kV max device cost (£)
- [Device ID x] HVDC min device cost (£)
- [Device ID x] HVDC max device cost (£)
- [Device ID x] 33kV min device number (Decimal count)
- [Device ID x] 33kV max device number (Decimal count)
- [Device ID x] 132kV min device number (Decimal count)
- [Device ID x] 132kV max device number (Decimal count)
- [Device ID x] HVDC min device number (Decimal count)
- [Device ID x] HVDC max device number (Decimal count)
- [Device ID x] 33kV cable cost (£)
- [Device ID x] 132 cable cost (£)
- [Device ID x] HVDC cable cost (£)
- [Device ID x] 33kV min cost of device and cable (£)
- [Device ID x] 33kV max cost of device and cable (£)
- [Device ID x] 132kV min cost of device and cable (£)

- [Device ID x] 132kV max cost of device and cable (£)
- [Device ID x] HVDC min cost of device and cable (£)
- [Device ID x] HVDC max cost of device and cable (£)
- [Device ID x] 33kV min installation cost (£)
- [Device ID x] 33kV max installation cost (£)
- [Device ID x] 132kV min installation cost (£)
- [Device ID x] 132kV max installation cost (£)
- [Device ID x] HVDC min installation cost (£)
- [Device ID x] HVDC max installation cost (£)
- [Device ID x] 33kV min decommissioning cost (£)
- [Device ID x] 33kV max decommissioning cost (£)
- [Device ID x] 132kV min decommissioning cost (£)
- [Device ID x] 132kV max decommissioning cost (£)
- [Device ID x] HVDC min decommissioning cost (£)
- [Device ID x] HVDC max decommissioning cost (£)
- [Device ID x] 33kV min output (MW)
- [Device ID x] 33kV max output (MW)
- [Device ID x] 132kV min output (MW)
- [Device ID x] 132kV max output (MW)
- [Device ID x] HVDC min output (MW)
- [Device ID x] HVDC max output (MW)
- [Device ID x] 33kV min overall costs (£)
- [Device ID x] 33kV max overall costs (£)
- [Device ID x] 132kV min overall costs (£)
- [Device ID x] 132kV max overall costs (£)
- [Device ID x] HVDC min overall costs (£)
- [Device ID x] HVDC max overall costs (£)
- [Device ID x] 33kV min revenue (£)
- [Device ID x] 33kV max revenue (£)
- [Device ID x] 132kV min revenue (£)
- [Device ID x] 132kV max revenue (£)
- [Device ID x] HVDC min revenue (£)
- [Device ID x] HVDC max revenue (£)
- [Device ID x] 33kV min profit/loss (£)

- [Device ID x] 33kV max profit/loss (£)
- [Device ID x] 132kV min profit/loss (£)
- [Device ID x] 132kV max profit/loss (£)
- [Device ID x] HVDC min profit/loss (£)
- [Device ID x] HVDC max profit/loss (£)
- [Device ID x] depth factor (scale factor)
- [Device ID x] distance factor (scale factor)

** Note [Device ID] can relate to any device within the database and therefore if 10 valid devices were discovered within the model, each file above would be present for each device ID from 1 to 10.*

G.5 Microsoft Access Data Tables

- Cables
- Company
- Deployment method factor
- Devices
- Devices at depth
- External random access files
- Installation depth factor
- Installation distance factor
- Material costs
- Model values
- Mooring costs
- Mooring method factor
- Ports
- Power stations
- PTO costs
- Ships

APPENDIX H MODEL TESTING, SUPPORTING MATERIAL

Within Chapter 5 there is a summary of the various initial test runs that were undertaken in this project. In order to allow the main text to flow, in depth detail of the first three test runs were placed within this appendix.

H.1 Batch results, first run

For a summary of the first run methodology and results please refer to *5.2 Batch results from first run*.

H.1.1 Device 5 (*Pelamis*)

Since the model produces a result for each cable type, each cable type for the device can be plotted, ranked by profit/loss result. Device 5 only produced 6 valid results for a 33kV cable, for which the model stipulates the site must be between the shore line and 29 km maximum. However, and more importantly, Pelamis, has to be within a maximum of 5 km from land. 3 of these sites are on the west coast of the Orkney Isles: 3rd 4th and 5th likely for development according to the model, 2 sites are between Mull and the islands of Coll and Tiree which are the 1st and 6th most likely for development. The second most likely according to the model is off the west coast of the Shetland Mainland.



Figure H.1 Device 5 (Pelamis wave device) showing the 3rd 4th and 5th ranked 33kV sites on the west coast of the Orkney Isles.



Figure H.2 Device 5 (Pelamis wave device) showing the 1st and 6th ranked 33kV sites in the Passage of Tiree between the islands of Mull and Coll/Tiree.



Figure H.3 Device 5 (Pelamis wave device) showing the 2nd ranked 33kV site in St Magnus Bay on the west coast of the Shetland Mainland.

The site found in Shetland is worth further explanation. The model does check for spare capacity at a landing point, however the values for each landing point in the

database were set to pass this capacity test, otherwise, so few sites would allow for a connection, and the model could not have been tested fully. This explains why Shetland (which is not connected to the mainland grid) allows for sites to be found, even although an array deployment is not possible at present.

At this point it is worth showing the testing methods that are available. As an example the location of the 6th most likely site (shown in *Figure H.2*) has been entered into the user method of the application to call the site details, with the resulting information shown in *Figure H.4*.

Site Details

Characteristics of Site

56 ° 35 ' 24 " -6 ° -27 ' -36 " Data row 295 Data column 125

Water Depth (GEBCO)	-56 Metres	Water Depth (DTI)	-50 Metres	Distance to Closest Shore	1.6 Nautical Miles	2.8 Kilometres
Closest Power Station Point to Point	Tiree Power Station			13.4 Nautical Miles		
				24.8 Kilometres		<input type="button" value="Show Station"/>
Closest Port Point to Point	Scarinish (Tiree)			12.2 Nautical Miles		
				22.6 Kilometres		<input type="button" value="Show Port"/>
Closest Power Station from Sector File	Tiree Power Station			13.4 Nautical Miles		
				24.8 Kilometres		
Closest Port from Sector File	Scarinish (Tiree)			12.2 Nautical Miles		
				22.6 Kilometres		

Wave Properties				Tidal Properties			
Annual Mean Hs	2.01 Metres	Summer Mean Hs	1.32 Metres	Annual Mean Power	0.08 kw/m2		
Annual Mean Tz	7.09 Seconds	Summer Mean Tz	5.94 Seconds	Mean Spring Peak Flow	0.88 ms-1		
Annual Mean Power	16.37 kw/m	Summer Mean Power	5.8 kw/m	Mean Neap Peak Flow	0.42 ms-1		
Autumn Mean Hs	2.12 Metres	Winter Mean Hs	2.56 Metres	Mean Spring Power	0.34 kw/m2		
Autumn Mean Tz	5.94 Seconds	Winter Mean Tz	7.57 Seconds	Mean Neap Power	0.03 kw/m2		
Autumn Mean Power	17.72 kw/m	Winter Mean Power	28.9 kw/m	Mean Spring Range	4.02 Metres		
Spring Mean Hs	1.78 Metres			Mean Neap Range	1.71 Metres		
Spring Mean Tz	6.83 Seconds						
Spring Mean Power	12.27 kw/m						

Device Selection Criteria

Find Devices, checked on: ☒ Water Depth (DTI) ☐ Distance from Land (KM) ☐ Resource (Annual Mean) ☐ Resource within: 10 %

Figure H.4 Characteristics of site screen showing the site details of the 6th most likely development sites between the islands of Mull and Coll and Tiree.

From the site details shown in *Figure H.4* it can be seen that there is a variation between the DTI and GEBCO data in terms of water depth. The model uses the DTI data for all calculations and therefore the site is equal to the maximum depth for Pelamis. This only proves the model is calling the correct water depth from the correct data field. For the Pelamis device the minimum and maximum depths are not known, only the ideal depth of 50 m is known, therefore only sites exactly 50 m will pass the water depth test.

The water depth from admiralty chart 2171 shows the water depth is ~70 m. The wave climate for Pelamis is known to be 27 kW/m and the site has an annual mean power of 16.37 kW/m, a summer mean power of 5.8 kW/m and a Winter Mean Power of 28.9 kW/m. The algorithm that checks the resource against the device within the model states that the ideal output of the device (27 kW/m) has to be within the seasonal extremes of the site which is the summer (5.8 kW/m) and winter (28.9 kW/m) mean power figures.

A check on some of the other details in Google Earth reveals the distance to the closest land is 4.01 km which is a variation compared to the DTI data, 2.8 km. The closest port, Scarinish (Tiree) is 22.63 km from the site (22.6 calculated by the model), and the closest power station (Tiree) being 24.81 km from the site (24.8 calculated by the model). Therefore, at this site a test of the various model calculations shows a strong correlation apart from the water depth and DTI distance to closest shore in that area.

The water depth issue is probably an anomaly with the resolution and the complex seabed in this area, so to gain more confidence in the working of the model, the 4th site in Orkney (shown in *Figure H.1*) was also checked for distance to land and water depth. The model for this site reads 50 m for the DTI water depth and 40 m for the GEBCO. The DTI figure has to read 50 m otherwise the Pelamis device would not have matched. The distance to land according to the model is 4.4 km with Google Earth showing 4.98 km. Chart 2249 shows a distance of 4.99 km and depth in the area is largely unsurveyed, however a 50 m contour line is adjacent (0.8 km) to the western (seaward) side of the site. The closest value to eastern landward side (1.8 km) shows 35 m.

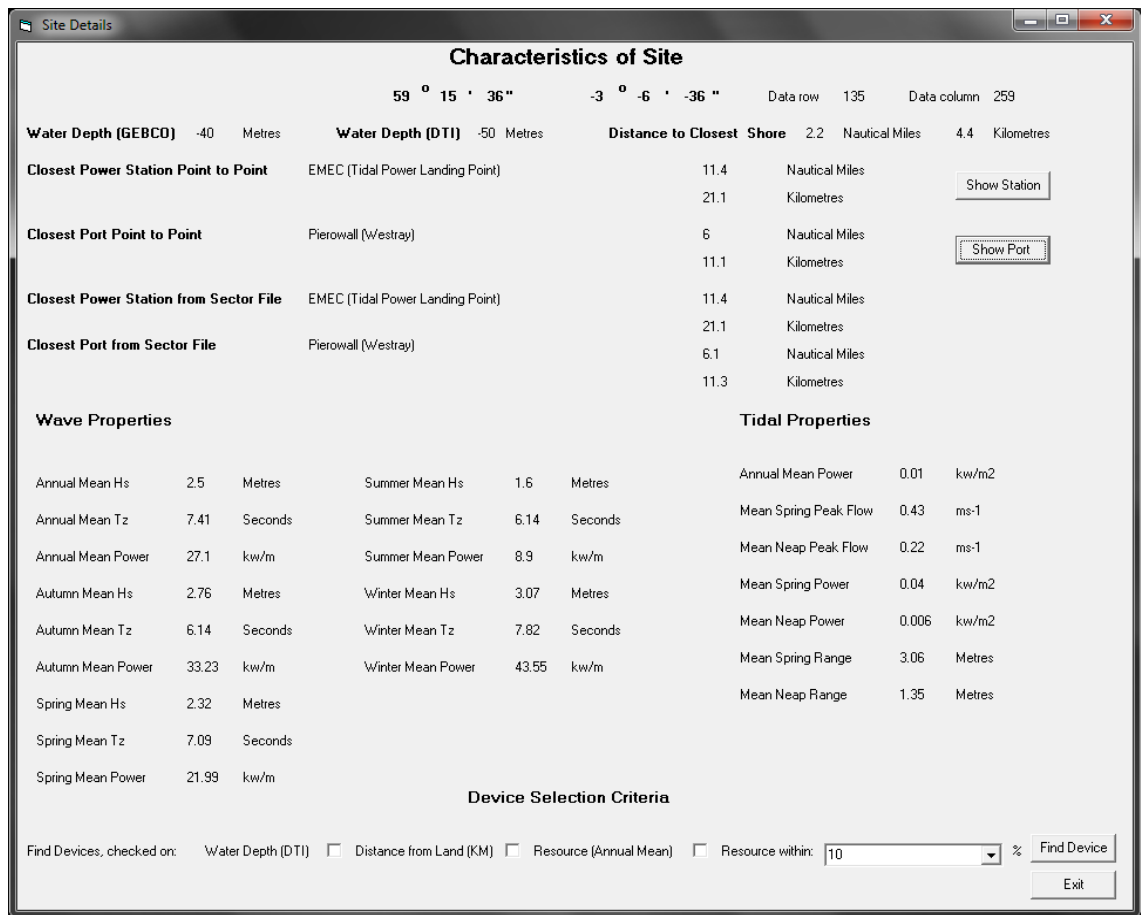


Figure H.5 Site Details of the 4th site, off Westray, Orkney.

This concludes the results for the 33kV cables. Moving onto the 132kV cables, only 6 valid sites were identified.

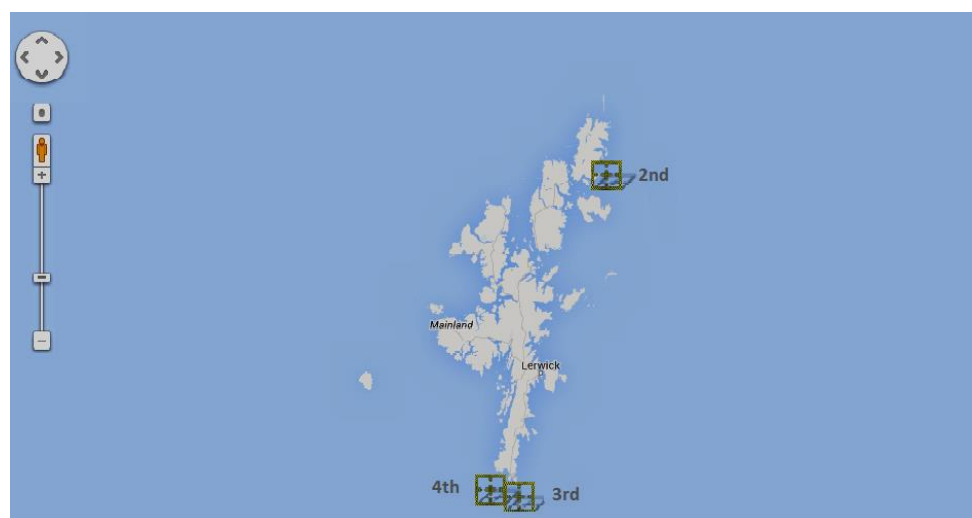


Figure H.6 Device 5 (Pelamis wave device) showing the 2nd, 3rd and 4th ranked 132kV sites around Unst and Sumburgh. Shetland, like many of the remote areas that follow,

only has a 33kV network so it is broadly assumed such a development could only take place with further developments to the onshore grid. The model for these tests is set so that onshore capacity is available to highlight the potential offshore sites.

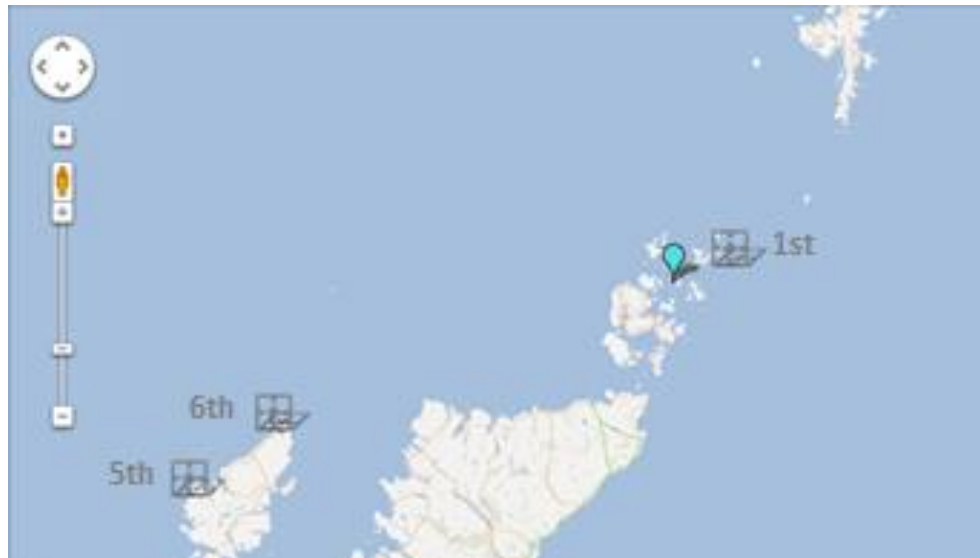


Figure H.7 Device 5 (Pelamis wave device) showing the 1st, 5th and 6th ranked 132kV sites off the west coast of Lewis, and Westray, Orkney. The distance (calculated in Google Earth) for the most feasible site in Orkney to the closest grid connection point is EMEC tidal site (plotted in blue) at 33.36 km.

Studying the results above, it may seem odd that the sites identified for the 33kV cable were different to the 132kV cable considering the device cannot be placed further than 5 km from the shore. However, the model states the 132 km cable has to be minimum 30 km and maximum 49 km in length from the a grid point, which in the model's case is a coastal power station or grid link in point. Therefore, this has allowed more remote locations to be identified out with the maximum range of 29 km of the 33kV cable. Moving onto the HVDC cable, only 2 valid sites were identified.



Figure H.8 Device 5 (Pelamis wave device) showing 1st and 2nd (all) ranked HVDC sites off Cape Wrath. The blue plot shown in this instance is to the closest grid connection point, Dounreay Power Station in Caithness 66.78 km.

As with the 132kV cable the HVDC also has its own parameters set within the model. For a site to have a HVDC cable then it must be minimum 50 km and maximum 500 km from the connection point. This again allows the model to find remote sites. It is interesting to observe that due to the Pelamis device having to be a maximum 5 km from the shore, the “remote sites” are only remote in the sense they are remote from grid connection points. If, for example, a grid connection point did exist at Cape Wrath then the sites would have been within the 33kV cable type. If Pelamis had the ability to work further offshore then sites further from the actual shore would have been identified, if these sites passed the various other model tests.

H.1.2 Device 75 (Test wave device)

Device 75 Test wave device, with favourable attributes allowed the model return 4498 valid sites for a 33kV cable. Plotted into Google Earth (and using Google Maps as the front end) are the top 10 most likely in terms of the cost analysis.



Figure H.9 Device 75 (Test wave device) showing the 5th, 6th, and 8th ranked 33kV sites around the Isle of Tiree.



Figure H.10 Device 75 (Test wave device) showing the 1st to 4th, 7th, 9th and 10th ranked 33kV sites around Eday in the Orkney Isles.

It can be seen from the above results that the test device is returning sites much closer to land. This is because in the database the minimum depth has been set to 5 m allowing shallow water sites to be tested by this device entry. If the 33kV cable type allowed a further distance from the shore then deeper water sites would have been shown as the device maximum depth has been set to 200 m. This is however shown when the longer

distance cables are plotted below. There is however a problem in that the 2nd and 3rd locations are actually on the shore. This again highlights the problem with the resolution of the underlying data. If the 3rd site is checked manually, the GEBCO data returns 16 m elevation on land, with the DTI returning 13 m of water.

Since this was an obvious concern, the original DTI water depth data (in its original format) was taken and loaded into the GIS package MapInfo to confirm the validity of data for this region, i.e. to test there has not been a flaw in the system used to undertake the various data formatting early in the project.

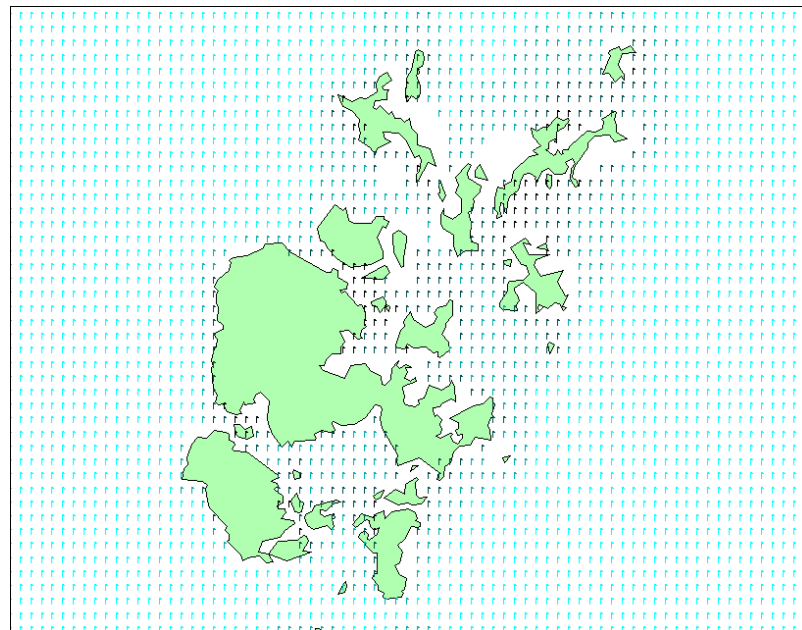


Figure H.11 showing the Orkney Islands with each point representing where a DTI water depth value exists. The scale values have been inverted so that lighter shades represent the higher values, this is to help highlight the shoreline regions that is the area of concern. It is also worth noting the various resource datasets are the same resolution, which will not show up the true potential of the tidal channels around Orkney.

The results show that the area around the Northern Isles of Orkney has various data anomalies, in that water depth data are plotted on land, and various areas at sea do not have any assigned data which confirms the theory that the resolution is problem, especially for intricate areas of shoreline such as Orkney. Moving to 132kV cable, 8177 sites were identified as valid. The top 10 places are plotted below.



Figure H.12 Device 75 (Test wave device) showing the 1st, 3rd, 6th and 9th ranked 132kV sites around the Shetland Isles.



Figure H.13 Device 75 (Test wave device) showing the 2nd, 4th, and 7th ranked 132kV sites around North Ronaldsay, Orkney. While the current development allows for different cable types, other current or future constraints such as the current regional grid network (currently, 33kV in Orkney) should be addressed in future developments.



Figure H.16 Device 75 (Test wave device) showing the 1st, 2nd and 5th ranked HVDC sites off the west coast of the Isle of Lewis. Note the other development sites off the Isle of Harris shown in Figure H.15, are the sites at the southern end of this plot. These have been included to show the relationship between the two sites.

The HVDC cables should also identify sites further offshore. The test wave device has a water depth set to 200 m and a 100 km distance from land. For reference, the device also has a wave resource set at 27 kW/m. The HVDC cable as mentioned before has a range of minimum 50 to maximum 500 km from a grid connection point. The offshore sites will however not show up in the top 10 listings as they are listed in order of cost, i.e. the top 10 sites are the 10 most likely in terms of economics, which means they will effectively be closer to the grid connection point, strategic port and so on. Therefore, to test the model is working as expected, the lowest 10 sites were also plotted.

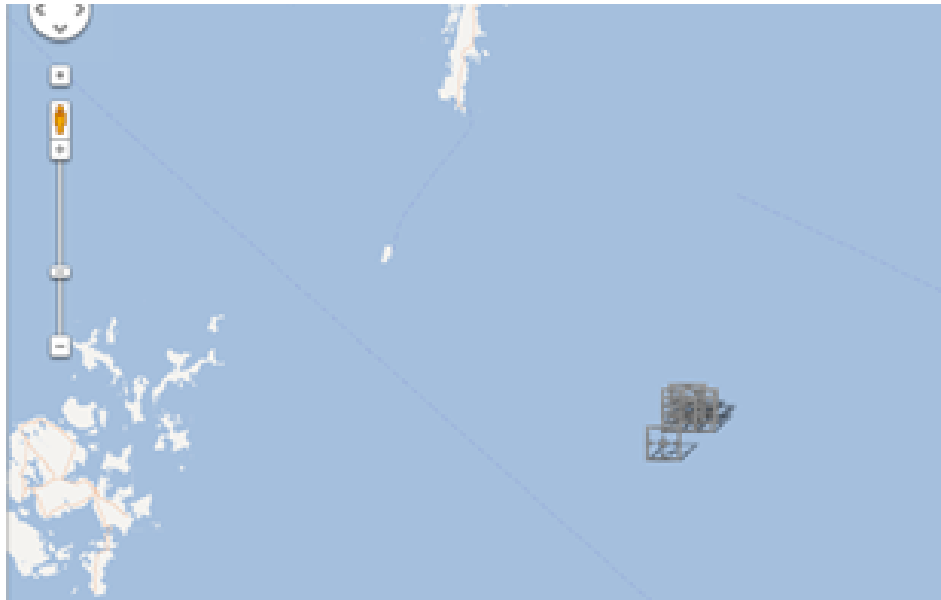


Figure H.17 Device 75 (Test wave device) showing the 31992nd to the 31985th ranked (i.e. 8 most unlikely) HVDC sites which are located in the North Sea. The furthest most point from significant land (which does not include Fair Isle) being 99.35 km.



Figure H.18 Device 75 (Test wave device) showing the 31984th and the 31983rd ranked HVDC sites which are located west of the Shetland Isles. The furthest most point from land being 81.46 km. Note within the DTI data an island such as Foula/Fair Isle are not considered to be a significant land mass and therefore the distance calculation was taken to the Shetland Mainland.

As predicted, the model has found sites further offshore. The furthest site in the North Sea is 128.05 km from Lerwick power station and the furthest site in the Atlantic is

110.51 km from Sullom Voe oil terminal. Therefore, it can be seen that the distance to land parameter set for the Test wave device (100 km) was a limiting factor (in comparison to the HVDC distance ability) for the device, and if the distance to land was set higher then sites further offshore may have been found, as the HVDC cable (set at 500 km) would allow this. However, as always, the various other criteria set by the model would also be a consideration.

Since individual plotting on Google Earth is restrictive for a device with a large return of results, the GIS package MapInfo was used to plot the entire Device 75 results which are shown in *Figure H.19*

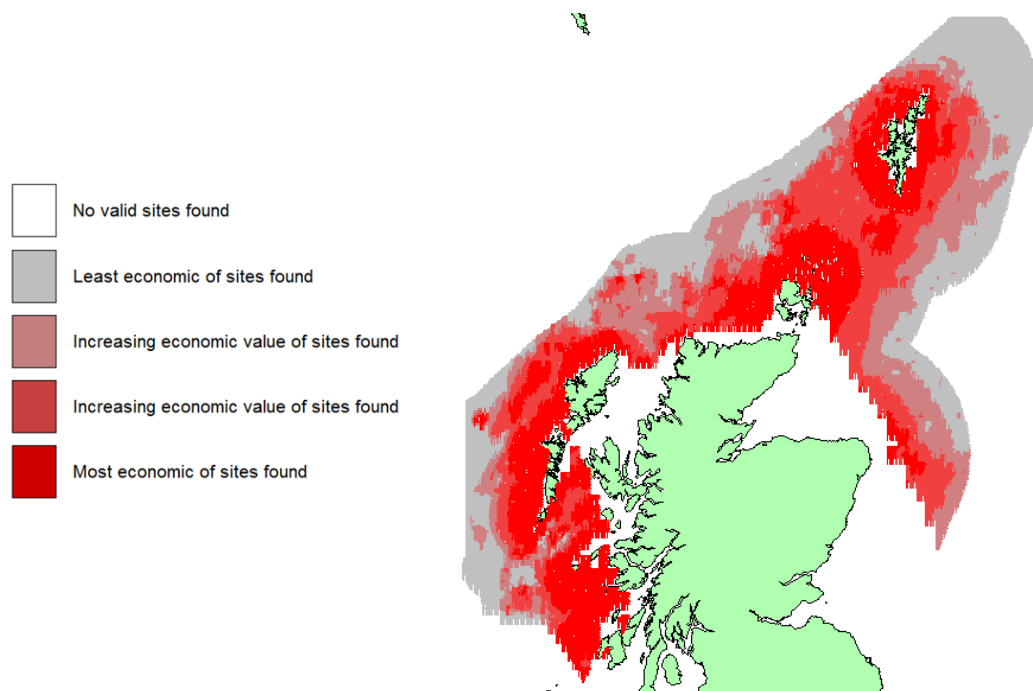


Figure H.19 entire cable and site results for Device 75 (Test wave device) showing the overall distribution. It is interesting to note that with the favourable device data, the return of sites was significant, however, there are still large areas where the device did not return any valid sites, such as the Minch, Moray Firth, the south east, and south west perimeters of the study area. This is due to these areas having a wave resource too low for the Test wave device which is set at 27 kW/m.

H.1.3 Device 76 (Test tidal device)

Device 76 (Test tidal device) has also been set with favourable attributes which allowed the model to return 444 valid sites for a 33kV cable. Plotted in Google Earth with

Google Maps *Figure H.20* shows the top 10 most likely in terms of the cost analysis. This is much less than for the test wave device which is expected, as high energy tidal sites are far fewer than wave. It is likely the resolution of the data will also be a contributing factor, as many high energy areas are close to shore where the coarse resolution is most apparent. Further testing was undertaken with the model data to establish if this explanation was valid.

The Test tidal device has the following properties set: water depth 200 m, tidal climate of 2 m per second and a maximum distance from land of 30 km.



Figure H.20 Device 76 (Test tidal device) with a 33kV cable, with the 1st to the 10th ranked 33kV sites, which are located within Hoy/Burra Sound, and the Falls of Warness in Orkney.

For the 132kV cable, 175 valid sites were identified. The top 10 sites are plotted in the figures below.



Figure H.21 Device 76 (Test tidal device) showing the 9th and 10th ranked 132kV sites which are located around Sanda Isle, off the Mull of Kintyre.



Figure H.22 Device 76 (Test tidal device) showing the 8th ranked 132kV site which is located in the Sound of Harris between the isles of Harris and Berneray/North Uist.



Figure H.23 Device 76 (Test tidal device) showing the 1st to 5th ranked 132kV sites which are located around North Ronaldsay in the north of the Orkney Isles. Note the 4th plot has ended up on land according to the Google Map background layer used for illustration purposes, which indicates a problem with the DTI bathymetry data at this location.

With the sites around North Ronaldsay it was found that one site (4th) is on the shore, again this is due to the resolution of the DTI data. The results from a manual check show that the DTI data has the site incorrectly listed as 25 meters of water with the GEBCO data showing 1 meter elevation. The DTI data also shows that the 4th site is 8.1 km from land which is roughly the distance to the island of Sanday to the south from the site. This shows that North Ronaldsay is not considered as a significant land mass and *Figure H.11* proves that the DTI data does include an actual land mass in this area.

The algorithm concerned with the plotting of the site, and the underlying data were checked at this point again, and it is safe to conclude that the algorithm is reading correctly. If the calculation was geographically inaccurate many other sites would have been found on land. Therefore, the various tests prove that the DTI water depth, GEBCO water depth and chart data do all correlate in terms of geographical location. This problem is caused by the resolution of the data, which is more apparent when close to shore.



Figure H.24 Device 76 (Test tidal device) with a 132kV cable, with the 6th and 7th most likely development sites which are located off Sumburgh Head, in the south of the Shetland mainland.

For the HVDC cables, 30 valid sites were identified. The top 10 places are plotted in the figures below. These are concentrated in two areas: the Little Minch off the Isle of Skye, and the Solway Firth off the Mull of Galloway.



Figure H.25 Device 76 (Test tidal device) showing the 1st, 2nd and 3rd ranked HVDC sites which are located in the Little Minch of the North coast of the Isle of Skye.



Figure H.26 Device 76 (Test tidal device), showing the 4th to 10th ranked HVDC sites which are located off the Mull of Galloway.

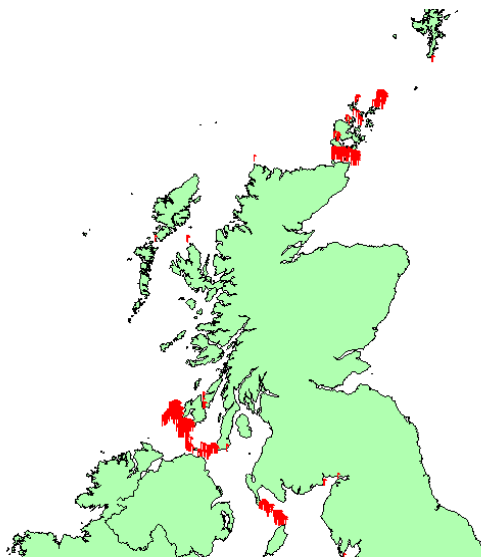


Figure H.27 showing a GIS (MapInfo) plot for all sites found for Device 76 Test tidal device.

H.2 Batch results, second run

For a summary of the second run methodology and results please refer to: 5.3 *Batch results after change to resource test logic (second run)*.

H.2.1 Device 5 (Pelamis)

The results show for Device 5 (Pelamis) the top 4 sites are the same for a 33kV cable, with the remaining 2 sites from the original 6 (North of Westray see *Figure H.1*, and the northern most in the passage of Tiree, see *Figure H.2*) now not passing to the final results. For a 132kV cable, only the site east of Shetland (see *Figure H.3*) and the site west of Lewis (see *Figure H.7*) survived, these sites are now ranked 1st and 2nd (*all*) as opposed to being 2nd and 5th originally. For a HVDC cable no valid sites were returned in the second run.

H.2.2 Device 75 (Test wave device)

For Device 75 (Test wave device) the top five, along with the 7th 9th, 10th 33kV positions have all now fallen, of which, the top four and the 7th, 9th, 10th were all in the highly tidal Falls of Warness in Orkney (see *Figure H.10*), with the last remaining being in the Passage of Tiree (see *Figure H.9*). The new top 10 are displayed in *Figures H.28* and *H.29* below.

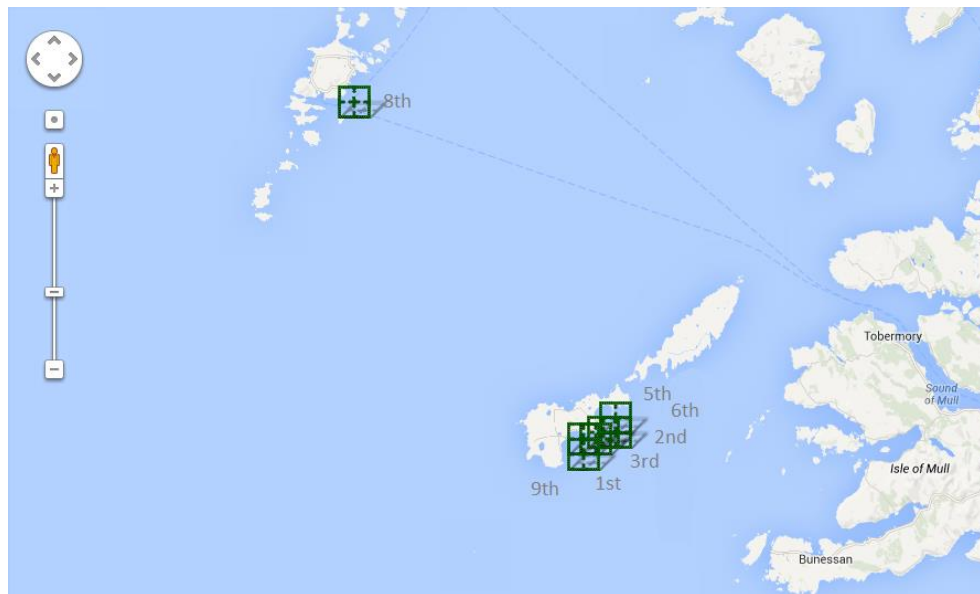


Figure H.28 Device 75 (Test wave device) showing the 1st, 2nd, 3rd, 5th, 6th, and 9th ranked 33kV sites in the Passage of Tiree, and 8th off Barra.



Figure H.29 Device 75 (Test wave device) showing the 4th, 7th and 10th ranked 33kV sites in the Orkney Isles.

For the 132 kV results the 2nd 4th and 7th sites (see *Figure H.13*) around North Ronaldsay in Orkney have been lost, as have the 3rd and 9th sites (see *Figure H.12*) off the south west Shetland mainland, along with the 1st site at the Out Skerries in Shetland. The new top 4 is made up of sites that were already in the top 10 with the remaining sites all new to the top 10, see *Figures H.30 and H.31*.

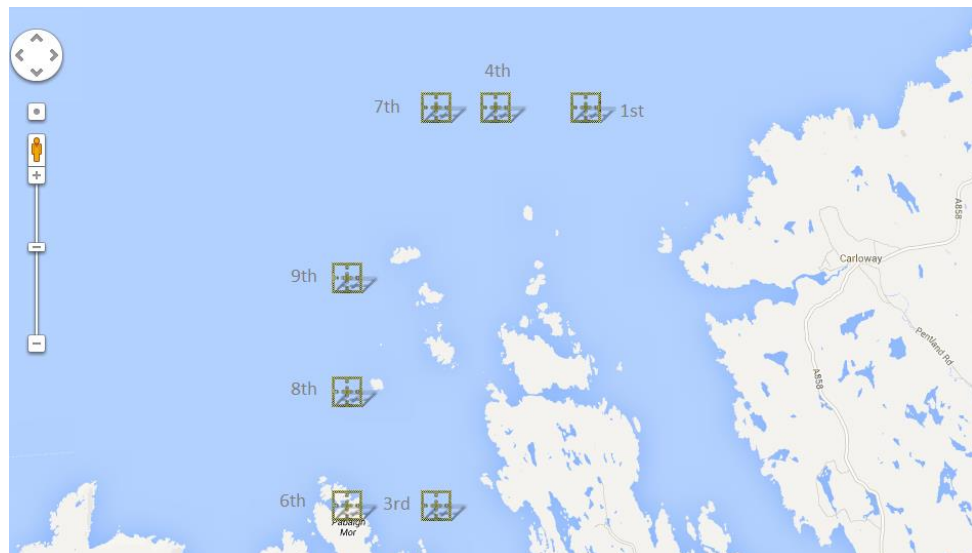


Figure H.30 Device 75 (Test wave device) showing the 1st, 3rd, 4th, 6th, 7th and 9th ranked 132 kV sites off the west coast of the Isle of Lewis.



Figure H.31 Device 75 (Test wave device) showing the 2nd, 5th and 10th ranked 132kV sites around the Shetland Isles.

For the HVDC cable, the previous rankings from 1st to 5th remain. Positions 6th, 7th, 9th and 10th have gone due to them being in the tidal areas (see *Figures H.15 and H.16*). The original position 8th is now 6th in the latest run, with new 7th to 10th positions.

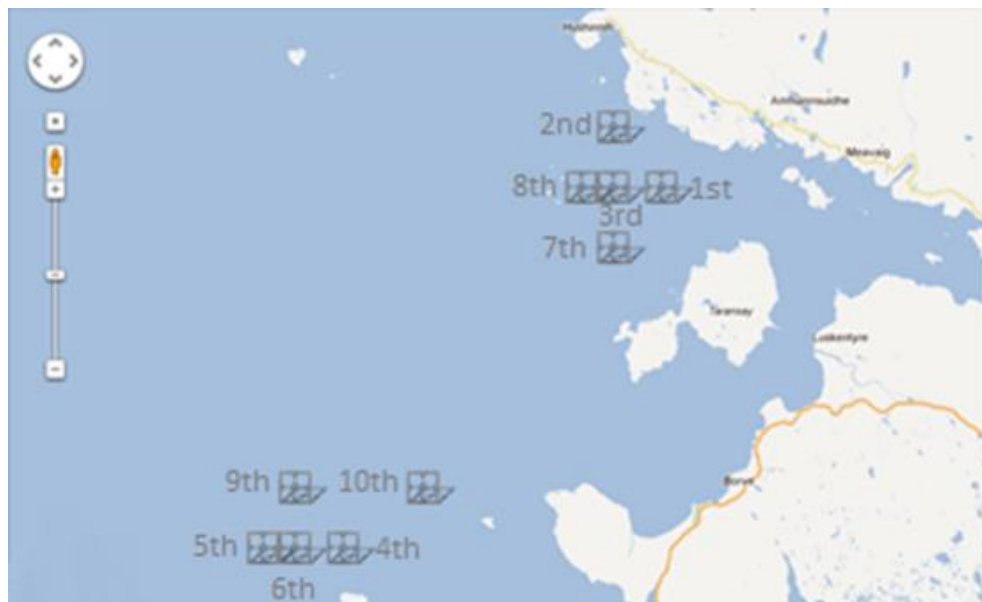


Figure H.32 Device 75 (Test wave device) showing the 1st to 10th ranked HVDC sites off the west coast of Harris and Lewis.

H.2.3 Device 76 (Test tidal device)

For device 76 (test tidal device) the alteration to the logic has marked effect with only 1 out of the previous 649 sites now passing the various tests to make it to the final profit/loss result. This is mainly due to the model not finding favourable sheltered sites as the resolution of the DTI data are not high enough within inland areas. The model is now ruling out exposed tidal sites where there is a high wave regime, however, with the resolution of the DTI data the model cannot find sheltered sites, which is a weakness of the present model. The only site to pass to the final profit/loss result is high in the Solway Firth off Annan. This site ranked 54th out of the 444 33kV sites found in the first run.



Figure H.33 Device 76 (Test tidal device) showing the only site to have passed to the final profit/loss results, which is off Annan in the upper reaches of the Solway Firth.

As expected, no new sites were found, as no actual data have been changed to allow this. The result were only ever going to be the sites found in the first run, minus the sites identified with conflicting tidal or wave resource.

H.3 Batch results, third run

For a summary of the third run methodology and results please refer to: *5.4 Batch results after changes, and additions to various database parameters (third run).*

H.3.1 Device 5 (Pelamis)

From the third run, with various changes made, there were no changes to the overall results for Device 5. Again only 6 sites (4 for 33kV and 2 for 132kV) were found and their rankings did not change.

H.3.2 Device 7 (OSPREDY)

The additional data entered for this device has allowed for it to pass to the final profit/loss indication results. The device has returned 6 sites: four 33kV and two 132kV.

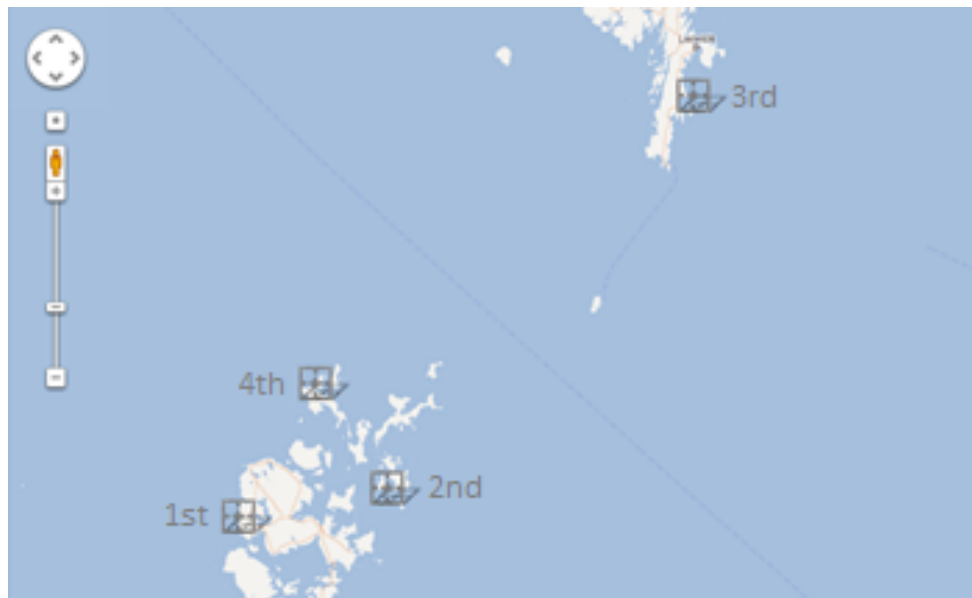


Figure H.34 Device 7 (OSPREDY) showing the 1st to 4th (all) ranked 33kV sites in the Orkney and Shetland Isles.



Figure H.35 Device 7 (OSPREDY) showing the 1st and 2nd (all) ranked 132kV sites off the Isle of Skye and Mull respectively.

H 3.3 Device 13 (Wave Star)

The additional data entered for this device has allowed for it to pass to the final profit/loss indication results. Device 13 (Wave Star) has come out very favourably, with 253 sites identified.



Figure H.36 Device 13 (Wave Star) showing the 1st to 10th ranked 33kV sites off the east coast off the Isle of Lewis, Dounreay, and around the Orkney Isles.

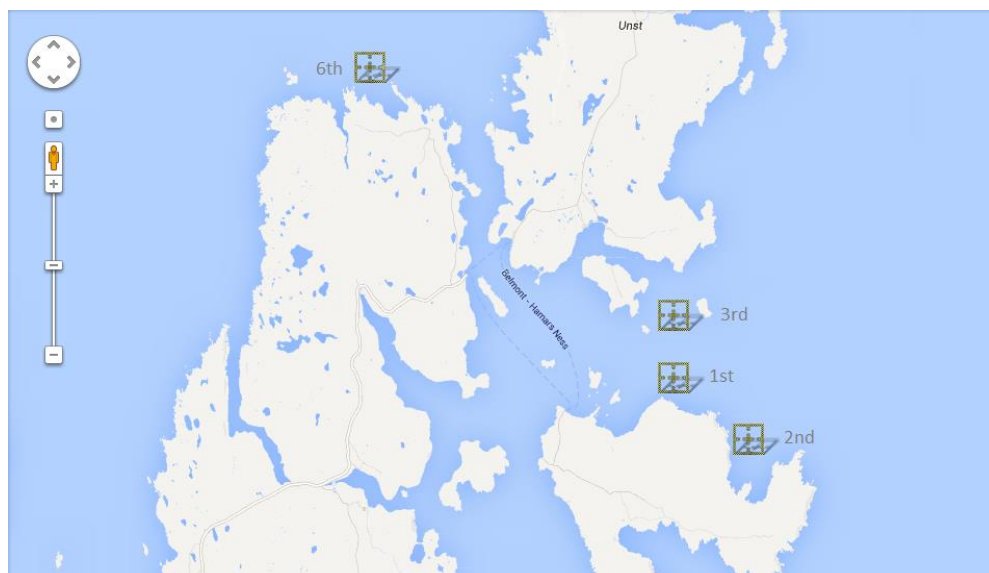


Figure H.37 Device 13 (Wave Star) showing the 1st, 2nd, 3rd and 6th ranked 132kV sites off the island of Yell, Unst and Fetlar in the Shetland Isles.



Figure H.38 Device 13 (Wave Star) showing the 5th and 7th ranked 132kV sites off the Buchan coast in the north east of Scotland.



Figure H.39 Device 13 (Wave Star) showing the 4th, 8th, 9th, and 10th ranked 132kV sites off the west coast off the Isle of Lewis.

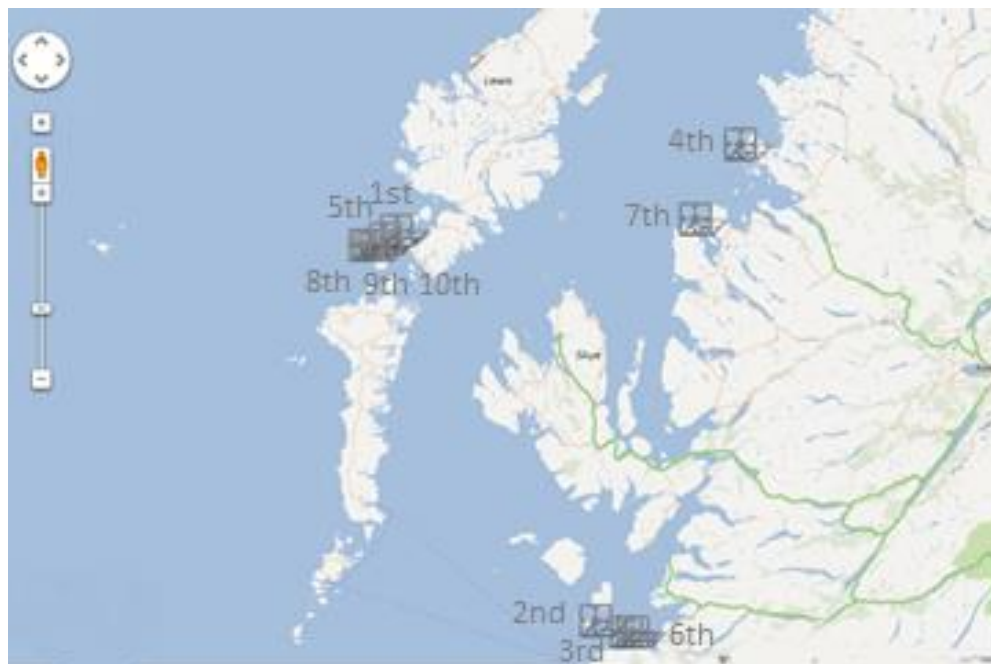


Figure H.40 Device 13 (Wave Star) showing the 1st to 10th ranked HVDC sites in various locations around the western coast and isles.

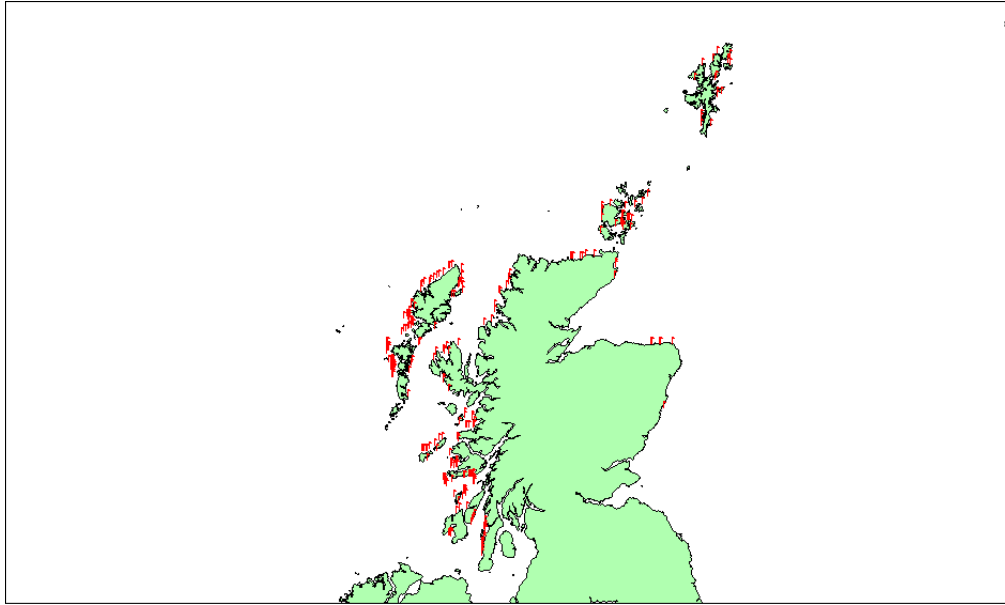


Figure H.41 Device 13 (Wave Star) showing the entire 253 results plotted with the GIS package MapInfo.

H.3.4 Device 45 (Marine Current Turbines)

The addition of additional device data and extra connection points has not allowed Device 45 to produced any final profit/loss results. While there were positive developments for all three physical attributes of : physical resource, distance from land, depth, there did not all coincide at the same site, and hence no valid union file was produced. A key reason for this was the device record stipulating 30 m of water (with no lower or upper range), a relatively high resource required (2.83 ms^{-1}), and some issues with the data resolution as discussed earlier. This is made more difficult considering the alteration to the code to overlook tidal sites with a conflicting wave resource, which discounts many large areas with a high tidal resource.

H.3.5 Device 47 (Tide1)

The additional data entered for this device have allowed it to pass to the final profit/loss indication results, returning a single 132kV result.



Figure H.42 Device 47 (TidE1) showing the 1st (only) ranked 132kV site off the Northern Irish coast.

H.3.6 Device 56 (Hammerfest Strøm)

The additional data entered for this device have allowed for it to pass to the final profit/loss indication results with 7 sites with a 132kV cable providing final results.



Figure H.43 Device 56 (Hammerfest Strøm) showing the 4th to 7th ranked 132kV sites off the north coast of the Isle of Man.

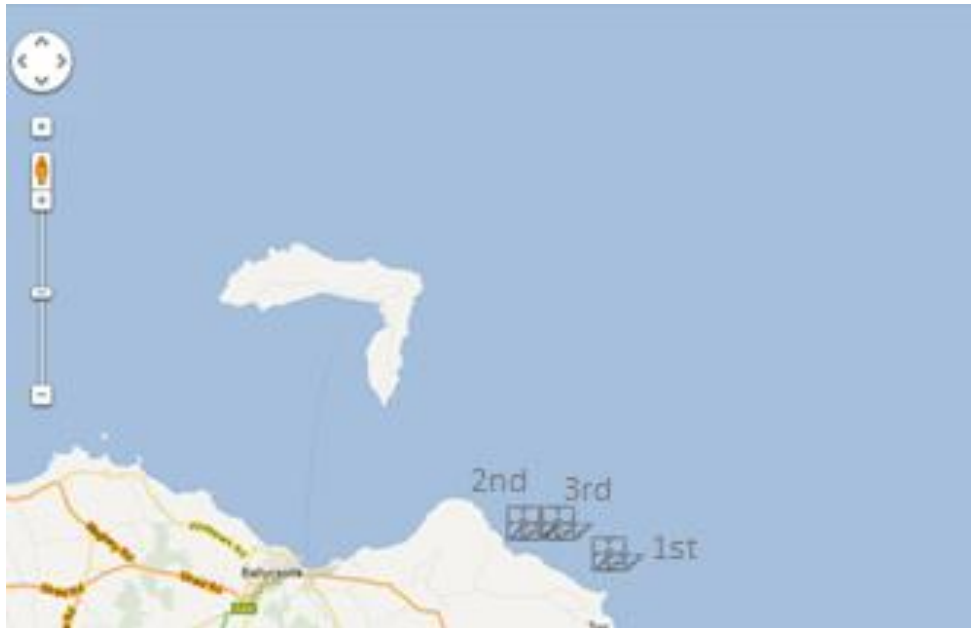


Figure H.44 Device 56 (Hammerfest Strøm) showing the 1st to 3rd ranked 132kV site off the Northern Irish coast.

H.3.7 Device 75 (Test wave device)

With this hypothetical device none of the actual device details have been changed, however the overall distribution has. There are more 33kV and 132kV sites and less HVDC sites. Overall there are 86 less results which was not expected and the reason for this is explained below. The reason for the increased 33kV and 132kV sites is due to the additions made to the connection points record. This is expected as providing an additional connection point will allow shorter cables from various sites, meaning the shorter cable methods will gain more sites at the expense of the sites that required HVDC cables previously.

The top 10 results were analysed and it was confirmed that for all cables the top 10 locations and rankings are the same. Therefore, to see exactly what changes the additional landing points made to the distribution of sites (and to explain why there are less sites overall) the data had to be analysed further with various scripts.

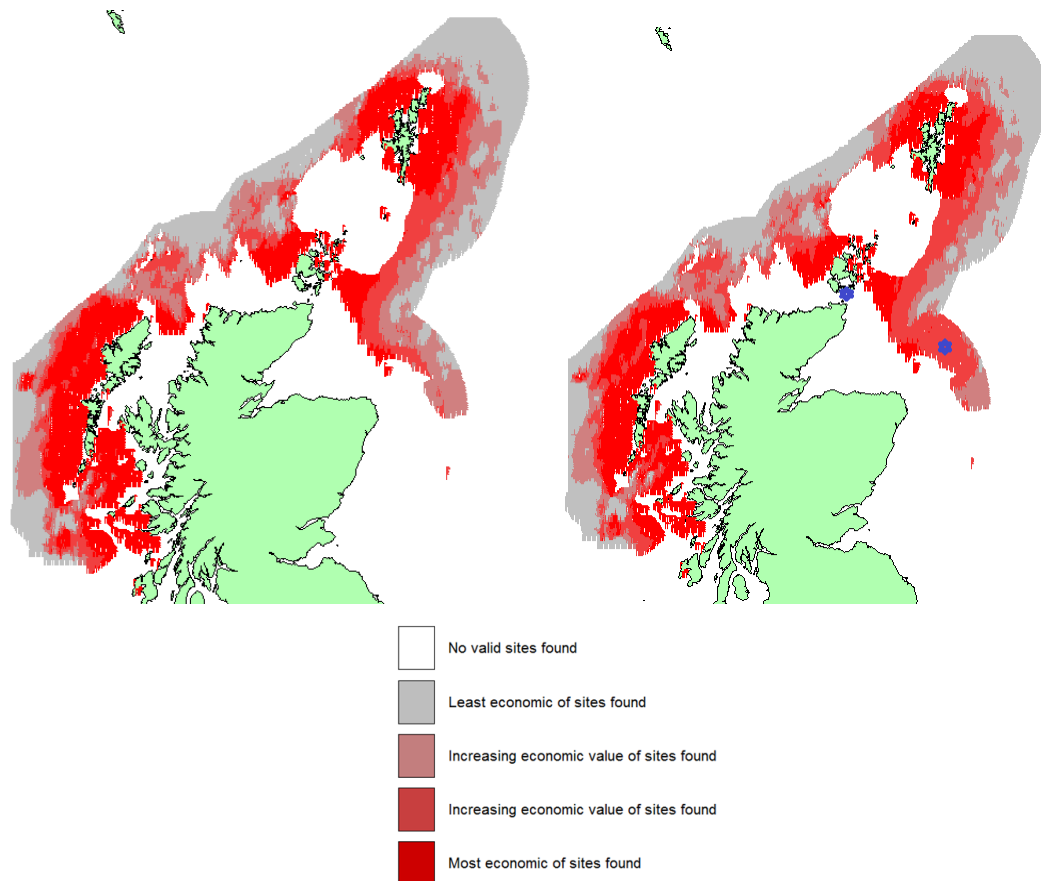


Figure H.45 showing an overall distribution of device 75 for the second (left) and third runs. At this resolution it is very difficult to spot the difference in device numbers, however the distribution change of the sites per cost can be identified with careful inspection which is the result of the newly added connection points (shown in blue) on the east coast.

As Device 75 returned the most valid sites in the second and third runs, a supplementary script was written to examine in more detail valid Device 75 sites with a 10 km² area around the two new landing points. In the case of the newly added Pentland Firth landing point no new sites were identified in this area for any cable type. The reason for this is that the area is a high tidal energy site, and the constraint of excluding wave devices in such locations incorporated in the second batch run excluded any such devices. At the second new landing point in the North Sea, the same 35 sites were found for Device 75 in both second and third runs. The important difference however was the change in the profit/loss indication results which show a reduction in cost (on average 17%) and a consequential increased profit/loss value for sites adjacent to the new landing points.

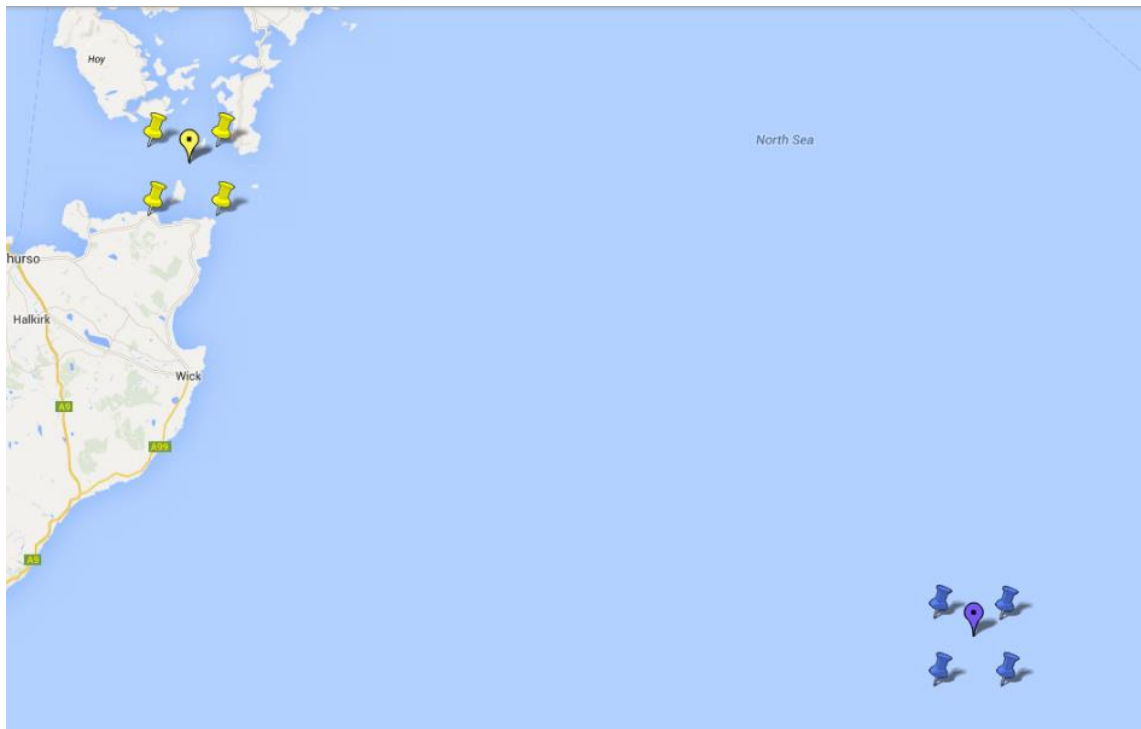


Figure H.46 showing the new landing points at the centre of defined study areas in the Pentland Firth (left yellow) and North Sea (right blue).

There is little difference in the actual profit/loss (cost) indication results for all sites in this area, less than 1% in both runs between the top site and the 35th site. However, within this new connection point area for the third run, there is a lower cost distribution between the top (1st) to bottom (35th) sites compared to the second run, i.e. the site profit/loss results return closer values in relation to each other than before. This change in distribution can be explained by the fact all the sites can now be linked to a close connection point via a 33kV cable, as opposed to a mainland point by a HVDC cable.

Another script was used to take a closer look at all the devices within the new North Sea 10 km test zone. From this the maximum and minimum cable values were stored to enable further analysis of the same 35 Device 75 sites. It was established that the maximum development scenario for the site and cable, showed a significantly lower cost indication in the third run (with the insertion of the new connection point) than previously. However, some of the values for the minimum development scenario were actually lower for the HVDC cable (second run) as the cable attributes within the database allows for a minimum of 200 MW to be installed for a HVDC cable rather than 400 MW for a 33kV. The cost of the devices, equalling 200 (1 MW each) for the minimum HVDC solution in the second run, was actually less than for the minimum

33kV solution using 400 (1 MW devices) in the third. It can also be established that the device cost is also a factor when considering the maximum HVDC output which is 600 MW, compared to the 33kV 500 MW within the database. The device cost has been shown to be significant in this exercise, as has the use of a particular cable with the associated maximum and minimum devices (in which these are the two values used by the model), as did the shorter allowed cable made available by the new connection point.

A further script was then used to extract the “difference” result from the both datasets, i.e. data that exists in one dataset but not the other, in order to explain why there are less sites overall. The results show data entries that exist for Device 75 (all cable types) in the second run that did not exist in the third run. This totalled 95, with a corresponding 9 entries in the third run set that does not exist in the second. This means 95 sites were found in second run were not available in the third run, and 9 new sites found in run three were not available in run two.

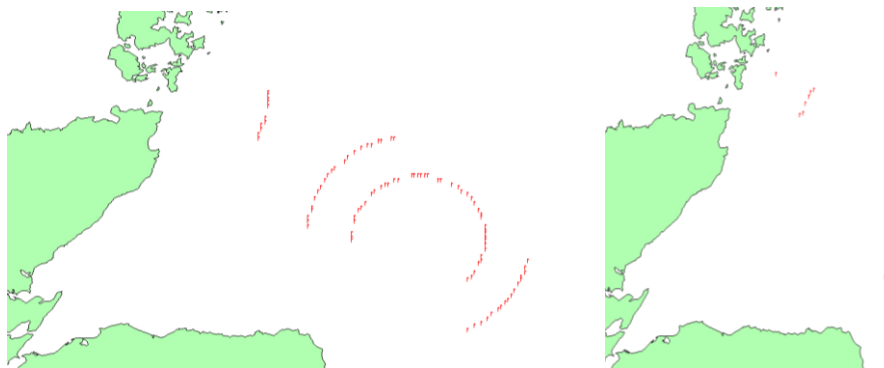


Figure H.47 showing the data difference between the second and third runs (left), and third and second runs (right). Each point indicates an individual site. 95 sites were identified in the second run which were not found in the third run, and 9 sites were identified in the third run which were not in the second run. These results point to a potential error in the coding/data used.

The circular array of points in the MapInfo display in *Figure H.47* represents the difference between the two batch runs which demonstrates the importance of using differential data to check the validity of results. The feature in the display was not expected and indicated an issue with the data entries within the database. Inspection of the cable dataset, indicated that the defined distances for the 33kv cables were: 0-29 km,

30-49 km for 132 kV, and above 50 km for HVDC cables. This meant that there were void areas between 29-30 km and 49-50 km. For example, one of the newly identified sites in the third run is 28.8 km east of the Pentland Firth test landing point to the east of Orkney. This site in the second run would have been out with the bounds of a 33kv cable to Kirkwall power station as at 29.67 km distance, it was greater than the upper threshold for the 33 kV cable, and too short for the 132kV cable. 6 more of the sites further to the east of the new Pentland Firth connection point were in the previous distance region between the 132kV and HVDC void for Kirkwall Power Station and Flotta landing points.

The two remaining new sites within the third run were 35.8 km from the newly added North Sea test landing point. Before the North Sea landing point was added, the closest landing point was St Fergus on the Buchan coast which was 49.55 km away, again in between the distance of a 132kV cable and a HVDC cable. The logic is working correctly in the model, however this is not an ideal situation as valid sites are being missed. Therefore, the data for the cables has been changed so there is no gap between the cable types and to ensure sites are not missed.

H.3.8 Device 76 (Test tidal device)

With this hypothetical device none of the actual device details have been changed, and this has not changed the overall result pattern in this run. There was only one result from the second batch run, which was found to be the unchanged in the third run.

APPENDIX I, LIST OF DEVICES MODEL USES

Devices processed by model, *in form*: Device ID number, name of device (company/developer)

I.1 Wave Devices

- 1 WaveDragon (Nissum Bredning), Wave Dragon ApS
- 2 WaveDragon (North Sea Design), Wave Dragon ApS
- 3 WaveDragon (36 kW/m Design), Wave Dragon ApS
- 4 Wave Dragon (Full Scale), Wave Dragon ApS
- 5 Pelamis, Ocean Power Delivery Limited (OPD)
- 6 EB Frond 0.5 MW, The Engineering Business Limited (EB)
- 7 OSPREY, Wavegen
- 8 OSPREY2, Wavegen
- 9 Mighty Whale, Japan Marine Science and Technology Centre (JAMSTEC)
- 10 Archimedes WaveSwing (AWS) Demonstration(2 MW), Archimedes WaveSwing (AWS) II BV
- 11 Archimedes WaveSwing (AWS) (6 MW) Archimedes WaveSwing (AWS) II BV
- 12 Floating Wave Power Vessel (FWPV), Sea Power International AB
- 13 Wave Star (North Sea Design)
- 14 Green Cat Turbine (GCT), Green Cat Renewables Ltd
- 15 Wave Rotor, Evelop BV
- 16 WaveRoller, Advanced Wave Energy (AW-Energy) Oy
- 17 Offshore Wave Energy Device (OWEL), Offshore Wave Energy Limited
- 18 SEAREV 0.5, Lecole Centrale de Nantes (Central School of Nantes)
- 19 WECA PDP500 (Wave Energy Conversion Activator-Pressure Dynamics Processor), DAEDALUS Informatics Ltd
- 20 Salter/Edinburgh Duck, Edinburgh University (The Wave Power Group)
- 21 PS Frog, Lancaster University Renewable Energy Group
- 22 Sea Clam, Coventry University
- 23 Cockerell Raft, Wavepower Limited (Sir Christopher Cockerell)
- 24 IPS Buoy, Interproject Service (IPS) AB
- 25 Sloped IPS Buoy, Edinburgh University (The Wave Power Group)

- 26 PowerBuoy, Ocean Power Technologies, Inc. (OPT)
- 27 Spurboy, Embley Energy Ltd
- 28 Wavebob, Clearpower Technology Limited
- 29 Swedish Hosepump, Technocean (Sweden)
- 30 McCabe Wave Pump, Hydam Technologies Ltd (Peter McCabe)
- 31 CETO Wave Energy Converter, Seapower Pacific PTY LTD
- 32 CETO Wave Energy Converter Full Scale, Seapower Pacific PTY LTD
- 33 Combined Energy System (CES), Ocean Motion International (OMI)
- 34 Slot-Cone Generator (SSG) Breakwater, WAVEenergyAS
- 35 Manchester Bobber, The University of Manchester Intellectual Property
- 36 C-Wave 1 MW, C-Wave Limited
- 37 AquaBuOY, AquaEnergy Group Limited
- 38 Float Pump, Danish Wave Power (DWP)
- 39 Bolgepumpen, Danish Maritime Institute
- 40 Hanstholm Buoy, Not Known
- 41 Oyster, AQUAMARINE POWER
- 42 Neptune Triton, Neptune Renewable Energy Ltd
- 43 bioWave, BioPower Systems Pty Ltd
- 44 Waveberg, Waveberg Development Limited
- 75 Test Wave Device, Hypothetical Test Company

I.2 Tidal Devices

- 45 Marine Current Turbines, Marine Current Turbines Limited (MCT)
- 46 Marine Current Turbines, Marine Current Turbines Limited (MCT)
- 47 TidE1, SMD Hydrovison
- 48 Stingray, The Engineering Business Limited (EB)
- 49 Stingray 2nd Generation, The Engineering Business Limited (EB)
- 50 Brian the Snail, Robert Gordon University (RGU)
- 51 Exim Stromturbiner, Sea Power International AB
- 52 Tidal Fence (Micro), Blue Energy Canada Inc
- 53 Venturi Energy Generating Apparatus (VEGA), Nova Energy Limited
- 54 Underwater Kite, Underwater Electric Kite (UEK)
- 55 Gorlov Helical Turbine, GCK Technology Inc

- 56 Hammerfest Strøm, Hammerfest Strøm
- 57 Ramsey sound Turbine, Tidal Hydraulic Generators Ltd
- 58 OpenCenter Submerged Composite Turbine, OpenHydro
- 59 TidalStream Semi-Submersible Turbine 2x1 MW Rotor, TidalStream
- 60 TidalStream Semi-Submersible Turbine 2x2 MW Rotor, TidalStream
- 61 SwanTurbine, SwanTurbines Limited
- 62 Offshore Energy Platform (KESC Bowsprit Tidal Generator), Kinetic Energy Systems, Inc.
- 63 KESC Bowsprit Tidal Generator, Kinetic Energy Systems Inc.
- 64 Tidal Generation Turbine, Tidal Generation Limited
- 65 Verdant Power Turbine, Verdant Power, LLC
- 66 Neptune Proteus Tidal Power Pontoon, Scottish and Southern Electric
- 67 Rotech (Lunar) Tidal Turbine (RTT) (1 MW), Lunar Energy Limited
- 68 Rotech (Lunar) Tidal Turbine (RTT) (2 MW), Lunar Energy Limited
- 69 Race Rocks, Pearson Collage Race Rocks Project
- 70 ENERMAR, Ponte di Archimede S.p.A. & Dpt of Aeronautical Eng, University of Naples
- 71 MYTHOS, Ponte di Archimede S.p.A. & Dpt of Aeronautical Eng, University of Naples
- 72 Loch Linnie Device, Scottish Nuclear, IT Power, and NEL
- 73 bioStream, BioPower Systems Pty Ltd
- 74 Leslie Pump, George Leslie, The Leslie Pump
- 76 Test Tidal Device, Hypothetical Test Company

I.3 Devices identified, but not processed by model due to insufficient data, *in form:* name of device, company/developer.

Wave Devices

- WavePlane, WavePlane Production A/S
- Oscillating Device, Arvid Nesheim
- Waterturbine, Arvid Nesheim
- Wave Plunger, Danish Maritime Institute
- WaveMill (Self Contained), Wavemill Energy Corp (WEC)

- Seawave Slot-Cone (SSG) Offshore Fixed Device, WAVEenergyAS
- Ocean Wave Energy Converter (OWEC), Ocean Wave Energy Company (OWECo)
- Oscillating Wave Surge Converter (OWSC), Queen's University Belfast and Manchester Metropolitan University
- WaveMaster, Ocean WaveMaster Limited
- DAM-ATOLL, Lockheed Missiles and Space Company
- Pneumatically Stabilized Platform (PSP), Float Incorporated
- Bristol Cylinder, Bristol University & Sir Robert McAlpine
- HRS Rectifier/Russell Lock, Hydraulics Research Station and Robert Russell
- Kaimei, Japan Marine Science and Technology Centre (JAMSTEC)
- Backward Bent Duct Buoy, Ryokuseisha Corporation
- Wave Rider, SeaVolt Technologies
- Wavemill Open Buoy Design, Wavemill Energy Corp (WEC)
- Directly Driven Linear Generators (DDLG), Seabased Energy AB
- Snapper, Ed Spooner & New and Renewable Energy Centre (NaREC)
- SEADOG Pump, Independent Natural Resources, Inc.(INRI)
- WaveBlanket, WindWavesAndSun.com
- SyncWave Power Resonator, SyncWave Energy Inc
- Polo, Edinburgh University (The Wave Power Group)
- FO³ SEEWEC, SEEWEC

Tidal Devices

- Rochester Venturi, HydroVenturi Ltd
- Scotrenewables Turbine, ScotRenewables
- GENTEC Venturi, Greenheat Systems
- Water Wall Turbine (Tidal), Water Wall Turbine Inc.
- Tidal Fence (Blue Energy Power System) 500 MW, Blue Energy Canada Inc.
- Tidal Fence (Mega Power System) 10 MW, Blue Energy Canada Inc.

APPENDIX J, PSEUDO CODE OF MODEL (AS BUILT)

FUNCTIONS, BATCH OPERATION

J.1 Determining a spatial distribution for each device determined by water depth

```

Declare dataStructure as column (520) with 4 digits per field
Declare outputStructure as column (520) with 2 digits per field
Open DTI Water Depth file
While Device.Name in Database Device Table <> End of File
  If (Device.Minimum Depth and Maximum Depth <> "") Then
    Open Device by Depth file for Random Access
    For each record row (j) (j = 1 to 450)
      Read into dataStructure the (j) record of the DTI Water Depth file
      For each column (i) (i = 0 to 519)
        If (dataStructure.column(i) <> "NA") Then
          If (dataStructure.column(i) >= Device.Max Depth & <= Device.Min
            Depth) then
            outputStructure.column(i) = "1"
          Else
            outputStructure.column(i) = "0"
          End if
        Else
          outputStructure(j).column(i) = "NA"
        End if
      Increment i
    Write outputStructure to (j) record of the Device by Depth file
    Increment j
  ElseIf (Device.Ideal Depth <> "") Then
    For each record row (j) (j = 1 to 450)
      Read into dataStructure the (j) record of the DTI Water Depth file
      For each column (i) (i = 0 to 519)
        If (dataStructure.column(i) <> "NA") Then
          If (dataStructure.column(i) = Device.IdealDepth) Then
            outputStructure.column(i) = "1"
          Else
            outputStructure.column(i) = "0"
          End if
        Else
          outputStructure(j).column(i) = "NA"
        End if
      Increment i
    Write outputStructure to (j) record of the Device by Depth file
    Increment j
  End if
Close Device by Depth file
Move to Next Device
Close DTI Water Depth file

```

J.2 Determining a spatial distribution for each device determined by resource

Declare dataStructure1 as column (520) with 5 digits per field
Declare dataStructure2 as column (520) with 5 digits per field
Declare dataStructure3 as column (520) with 4 digits per field
Declare dataStructure4 as column (520) with 4 digits per field
Declare outputStructure as column (520) with 2 digits per field
Open DTI:Winter Mean Wave Power, Summer Mean Wave Power, Mean Spring Peak Flow, Mean Neap Peak Flow files

```
While Device.Name in Database Device Table <> End of File
  If (Device.Wave Climate <> "" & Device.Type = "WAVE") Then
    Open Device by Resource file for Random Access
    For each record row (j) (j = 1 to 450)
      Read into dataStructure1 the (j) record of the DTI Winter Mean Wave Power (j)
      Read into dataStructure2 the(j) record of the DTI Summer Mean Wave Power (j)
      For each column (i) (i = 0 to 519)
        If (dataStructure1.column(i)<> "NA") Then
          If (devices.Wave Climate <= dataStructure1.column(i) and >=
            dataStructure2.column(i) ) then
            outputStructure.column(i) = "1"
          Else
            outputStructure.column(i) = "0"
          End if
        Else
          outputStructure.column(i) = "NA"
        End if
        Increment i
      Write outputStructure to (j) record of the Device by Resource file
    Increment j
  ElseIf (Device.Tidal Climate<> "" & Device.Type = "TIDAL") Then
    For each record row (j) (j = 1 to 450)
      Read into dataStructure3 the (j) record of the DTI Mean Spring Peak Flow file
      Read into dataStructure4 (j) record of the DTI Mean Neap Peak Flow file
      For each column (j) (i = 0 to 519)
        If (dataStructure3.column(i) <> "NA") Then
          If (Device.Tidal Climate <= dataStructure3.column(i) & >=
            dataStructure4.column(i)) Then
            outputStructure.column(i) = "1"
          Else
            outputStructure.column(i) = "0"
          End if
        Else
          outputStructure.column(i) = "NA"
        End if
        Increment i
      Write outputStructure to (j) record of the Device by Resource file
    Increment j
  End if
  Close Device by Resource file
  Move to Next Device
```


Close DTI: Winter Mean Wave Power, Summer Mean Wave Power, Mean Spring Peak Flow, Mean Neap Peak Flow files

J.3 Determining a spatial distribution for each device determined by distance to land

```
Declare dataStructure as column (520) with 6 digits per field
Declare outputStructure as column (520) with 2 digits per field
Open DTI Distance to Land file
While Device.Name in Database Device Table <> End of File
  If (Device.Distance to Land<> "") Then
    Open Device by Distance file for Random Access
    For each record row (j) (j = 1 to 450)
      Read into dataStructure the (j) record of the DTI Distance to Land file
      For each column (i) (i = 0 to 519)
        If (dataStructure.column(i) <> "NA") Then
          If (dataStructure.column(i) to km <= Device.Distance to land) then
            outputStructure.column(i) = "1"
          Else
            outputStructure.column(i) = "0"
          End if
        Else
          outputStructure(j).column(i) = "NA"
        End if
      Increment i
    Write outputStructure to (j) record of the Device by Distance file
  Increment j
End if
Close Device by Distance file
Move to Next Device
Close DTI Distance to Land file
```

J.4 Determining an overall spatial distribution for each device determined by water depth, resource, and distance to land

```
Declare dataStructure1 as column (520) with 2 digits per field
Declare dataStructure2 as column (520) with 2 digits per field
Declare dataStructure3 as column (520) with 2 digits per field
Declare outputStructure as column (520) with 2 digits per field

While Device.Name in Database Device Table <> End of File

  If (Device by Depth, Resource and Distance files<> "") then
    Open Device by: Depth, Resource, Distance files
    Open Device by Distance file for Random Access

    For each record row (j) (j = 1 to 450)
      Read into dataStructure the (j) record of the DTI Distance to Land file
```

```

For each column (i) (i = 0 to 519)
If (dataStructure.column(i) <> "NA") Then
    If (dataStructure1.column(i) = "1" & dataStructure2.column(i) = "1" &
        dataStructure3.column(i) = "1") then
        outputStructure.column(i) = "1"
    Else
        outputStructure.column(i) = "0"
    End if
Else
    outputStructure(j).column(i) = "NA"
End if
Increment i
Write outputStructure to (j) record of the Device by Union file
Increment j
End if

Close Device by Union file
Close DTI Distance to Land file
Move to Next Device

```

J.5 Constructing a distance matrix from each site to closest power station

```

Declare dataStructure as column (520) with 4 digits per field
Declare outputStructure1 as column (520) with 5 digits per field
Declare outputStructure2 as column (520) with 3 digits per field

Open DTI Annual Mean Wave Height file
Open Power Distance file for Random Access
Open Power ID file for Random Access
Set Latitude Seconds to 221370, location of 61° 29.5' North

For each record row (j) (j = 1 to 450)
    Set Longitude Seconds to -34515, location of 9° 35' 25" West
    Read into dataStructure the (j) record of the DTI Annual Mean Wave Height
    For each column (i) (i = 0 to 519)
        Set shortestDistance to 10000
        Set boolean marker to false
        If (dataStructure.column(i) <> "NA") Then
            outputStructure1.column(i) = "NA"
            outputStructure2.column(i) = "NA"
        Else
            While Power Station.Name in Database Device Table <> End of File
                Calculate Latitude Difference from Latitude Seconds – Power
                Stations.LatitudeSeconds
                Calculate Longitude Difference from Longitude Seconds – Power
                Stations.Longitude Seconds
                Save Power Stations.Latitude Seconds as Holding Degree Value
                Call Calculate Distance Method (passing: Latitude Difference, Longitude
                Difference, Holding Degree Value, Latitude Seconds) Returning Overall
                Distance
            End While
        End If
    End For
    Write outputStructure1 to (j) record of the Device by Union file
    Write outputStructure2 to (j) record of the Device by Union file
    Increment j
End For

```

```

    If (Overall Distance < Shortest Distance) Then
        While Cables in Database <> End of File
            If (Overall Distance > Cables.Min Length and < Cables.Shortest Length)
                Then
                    If (Cables.Max Output < Power Station.Capacity) then
                        Shortest Distance = Overall Distance
                        Shortest Location = Power Stations.ID
                        Set boolean marker to true
                    End if
                End if
            Move to next Cable
        End if
        Move to next Power Station

        If (marker =true) then
            outputStructure1.column(i) = Shortest Distance
            outputStructure2.column(i) = Shortest Location
        End if
        outputStructure1.column(i) = na
        outputStructure2.column(i) = na
    End if
    Increment Longitude Seconds by 90
    Increment i
    Write outputStructure1 to (j) record of Power Distance file
    Write outputStructure2 to (j) record of Power ID file
    Decrement Latitude Seconds by 60
    Increment j
    Close DTI Annual Mean Wave Height file
    Close Power Distance file
    Close Power ID file

```

J.6 Construct a distance matrix from each site to closest port

This method is very similar to that of *J.5 Constructing a distance matrix from each site to closest power station*. The main difference is this method is calculating the port datasets. There is also a slight difference in logic as this method does not look at a spare capacity figure as with the power stations, and that the method saves the first port as a distance benchmark which is not undertaken for power stations.

```

Declare dataStructure as column (520) with 4 digits per field
Declare outputStructure1 as column (520) with 5 digits per field
Declare outputStructure2 as column (520) with 3 digits per field

```

```

Open DTI Annual Mean Wave Height file
Open Port Distance file for Random Access
Open Port ID file for Random Access
Set Latitude Seconds to 221370, location of 61° 29.5' North

```

```

For each record row (j) (j = 1 to 450)

```

```

Set Longitude Seconds to -34515, Location of 9° 35' 25'' West
Read into dataStructure the (j) record of the DTI Annual Mean Wave Height
For each column (i) (i = 0 to 519)
  Set boolean marker to false
  If (dataStructure.column(i) <> "NA") Then
    outputStructure1.column(i) = "NA"
    outputStructure2.column(i) = "NA"
  Else
    While Port.Name in Database Device Table <> End of File
      Calculate Latitude Difference from Latitude Seconds – Port.LatitudeSeconds
      Calculate Longitude Difference from Longitude Seconds – Port.Longitude
      Seconds
      Save Port.Latitude Seconds as Holding Degree Value
      Call Calculate Distance Method (passing: Latitude Difference, Longitude
      Difference, Holding Degree Value, Latitude Seconds) Returning Overall
      Distance

      If (marker = True) Then
        If (Overall Distance < Shortest Distance) Then
          Shortest Distance = Overall Distance
          Shortest Location = Port.ID
        End if
      Else
        Shortest Distance = Overall Distance
        Shortest Location = Port.ID
      End if
      Set boolean marker to true
      Move to next Port Station
      outputStructure1.column(i) = Shortest Distance
      outputStructure2.column(i) = Shortest Location
    End if
    Increment Longitude Seconds by 90
  Increment i
  Write outputStructure1 to (j) record of Port Distance file
  Write outputStructure2 to (j) record of Port ID file
  Decrement Latitude Seconds by 60
Increment j
Close DTI Annual Mean Wave Height file
Close Port Distance file
Close Port ID file

```

J.7 Calculate cable costs for each site against valid location for each device

```

Declare dataStructure1 as column (520) with 2 digits per field
Declare dataStructure2 as column (520) with 5 digits per field
Declare CableCostArray array (0 to 2) as column (520) with 9 digits per field
Declare CurrentFileName array (0 to 2) as String

```

```

While Device.Name in Database Device Table <> End of File
  Open Device by Union file
  If (Device by Union file <> "") Then

```

```

Open Power Distance file
Open Cable Costs 33kV file for Random Access as CurrentFileName(0)
Open Cable Costs 132kV file for Random Access as CurrentFileName(1)
Open Cable Costs HVDC file for Random Access as CurrentFileName(2)

For each record row (j) (j = 1 to 450)
  Read into dataStructure1 the (j) record of the Device by Union file
  Read into dataStructure1 the (j) record of thePower Distance file
  For each column (i) (i = 0 to 519)
    If (dataStructure1.column(i) = "NA") Then
      For each x (x = 0 to 2)
        cableCostArray(x).column(i) = "NA"
      Next x
    If (dataStructure1.column(i) = "na") Then
      For each x (x = 0 to 2)
        cableCostArray(x).column(i) = "na"
      Next x
    ElseIf (dataStructure1.column(i) = "0") Then
      For each x (x = 0 to 2)
        cableCostArray(x).column(i) = "0"
      Next x
    Else
      Set count to 0
      While Cables.Name in Database Device Table <> End of File
        If (theStructure2.column(i) to km >= Cables.Min Length km) &
           theStructure2.column(i) to kilometers<= Cables.Max Length km) Then
          cableCostArray(count).column(i) = theStructure2.column(i) to
          km * Cables.Overall Cost
        Else
          cableCostArray(count).column(i) = "na"
        End if
        increment count
        Move to next Cable
      End if
      Increment i

      For each x (x = 0 to 2)
        Write cableCostArray(x) to (j) record of CurrentFileName(x)
      Increment x
    Increment j

  Close Power Distance file
  Close Cable Costs 33kV file for Random Access
  Close Cable Costs 132kV file for Random Access
  Close Cable Costs HVDC file for Random Access

Move to next Device

```

J.8 Calculate the number of devices required and device output at a given site

Declare dataStructure1 as column (520) with 2 digits per field
Declare dataStructure2 as column (520) with 5 digits per field
Declare CableInputsArrayarray (0 to 5) as column (520) with 5 digits per field
Declare OutputValueArray array (0 to 5) as column (520) with 3 digits per field
DecareouputFile array (0 to 5) as String
Declare CurrentFileName array (0 to 7) as String

While Device.Name in Database Device Table <> End of File

If (Device by Union file<> "") Then

Open Device by Union file as CurrentFileName(0)

Open Power Distance file as CurrentFileName(1)

Open Device 33kV Min Number file for Random Access as CurrentFileName(2)

Open Device 33kV Max Number file for Random Access as CurrentFileName(3)

Open Device 132kV Min Number file for Random Access as CurrentFileName(4)

Open Device 132kV Max Number file for Random Access as CurrentFileName(5)

Open Device HVDC Min Number file for Random Access as CurrentFileName(6)

Open Device HVDC Max Number file for Random Access as CurrentFileName(7)

Open Device 33kV Min Output Number file for Random Access as outputFile(0)

Open Device 33kV Max Output Number file for Random Access as outputFile(1)

Open Device 132kV Min Output Number file for Random Access as outputFile(2)

Open Device 132kV Max Output Number file for Random Access as outputFile(3)

Open Device HVDC Min Output Number file for Random Access as outputFile(4)

Open Device HVDC Max Output Number file for Random Access as outputFile(5)

For each record row (j) (j = 1 to 450)

Read into dataStructure1 the (j) record of the Device by Union file

Read into dataStructure2 the (j) record of the Power Distance file

For each column (i) (i = 0 to 519)

For each x (x = 0 to 5)

cableInputsArray(x).column(i) = ""

outputValueArray(x).column(i) = ""

Next x

If (dataStructure1.column(i) = "NA") Then

For each x (x = 0 to 5)

cableInputsArray(x).column(i) = "NA"

outputValueArray(x).column(i) = "NA"

Next x

Elseif (dataStructure1.column(i) <> "0" or dataStructure2.colum(i) = "na") Then

For each x (x = 0 to 5)

cableInputsArray(x).column(i) = "na"

outputValueArray(x).column(i) = "na"

Next x

Else

Set count to 0

While Power Cables in Database Device Table <> End of File

If (Cables.Min Length <theStructure2.column(i) to km &

Cables.Max Length km > theStructure2.column(i) to kilometers Then

cableInputsArray(count).column(i) = Cables.Min Output /

Devices.output

```

        cableInputsArray(count + 1).column(i) = Cables.Max Output /
        Devices.output
        outputValueArray (count).column(i) =
        cableInputsArray(count).column(i) * Devices.output
        outputValueArray (count + 1).column(i) =
        cableInputsArray(count + 1).column(i) * Devices.output
    Else
        cableInputsArray(count).column(i) = "na"
        cableInputsArray(count + 1).column(i) = "na"
        outputValueArray(count).column(i) = "na"
        outputValueArray(count + 1).column(i) = "na"
    End if
    increment count by 2
    Move to next Cable
End if
Increment i

For each x (x = 0 to 5)
    Write cableInputsArray(x) to (j) record of CurrentFileName(x + 2)
    Write outputValueArray(x) to (j) record of outputFile(x)
Increment x
Increment j

Close Device by Union file
Close Power Distance file
Close Device 33kV Min Number file
Close Device 33kV Max Number file
Close Device 132kV Min Number file
Close Device 132kV Max Number file
Close Device HVDC Min Number file
Close Device HVDC Max Number file
Close Device 33kV Min Output Number file
Close Device 33kV Max Output Number file
Close Device 132kV Min Output Number file
Close Device 132kV Max Output Number file
Close Device HVDC Min Output Number file
Close Device HVDC Max Output Number file
Move to next Device

```

J.9 Calculate the device cost for a given valid site

```

Declare dataStructure array (0 to 5) as column (520) with 5 digits per field
Declare deviceCostArray array (0 to 5) as column (520) with 9 digits per field
DecareoutputFile array (0 to 5) as String
Declare CurrentFileName array (0 to 5) as String

```

```

While Device.Name in Database Device Table <> End of File
    If (Device 33kV Min Number file <> "") Then
        Set Device 33kV Min Number file as CurrentFileName(0)
        Set Device 33kV Max Number file as CurrentFileName(1)
        Set Device 132kV Min Number file as CurrentFileName(2)
    
```

Set Device 132kV Max Number file as CurrentFileName(3)
Set Device HVDC Min Number file as CurrentFileName(4)
Set Device HVDC Max Number file as CurrentFileName(5)

Set Device 33kV Min Cost file for Random Access as outputFile(0)
Set Device 33kV Max Cost file for Random Access as outputFile(1)
Set Device 132kV Min Cost file for Random Access as outputFile(2)
Set Device 132kV Max Cost file for Random Access as outputFile(3)
Set Device HVDC Min Cost file for Random Access as outputFile(4)
Set Device HVDC Max Cost file for Random Access as outputFile(5)

```

For each x (x = 0 to 5)
  Open CurrentFileName(x)
  Open outputFile(x)
  For each record row (j) (j = 1 to 450)
    Read into dataStructure(x) the (j) record of the file set at CurrentFileName(x)
    For each column (i) (i = 0 to 519)
      deviceCostArray(x).column(i) = ""
      If (Devices.device cost > 0) Then
        If (dataStructure(x).column(i) = "NA") Then
          deviceCostArray(x).column(i) = "NA"
        ElseIf (dataStructure(x).column(i) = "na") Then
          deviceCostArray(x).column(i) = "na"
        Else
          deviceCostArray(x).column(i) = Devices.device cost *
            dataStructure(x).column(i)
        End if
      Else
        deviceCostArray(x).column(i) = "na"
      End if
    Increment i
    Write deviceCostArray(x) to (j) record of outputFile(x)
  Increment j
  Close outputFile(x)
  Close CurrentFileName(x)
Increment x
End if
Move to next Device

```

J.10 Add device costs to cable costs

Declare dataStructure1 array (0 to 2) as column (520) with 9 digits per field
Declare dataStructure2 array (0 to 5) as column (520) with 9 digits per field
Declare costArray array (0 to 8) as column (520) with 9 digits per field
Declare CurrentFileName1 array (0 to 2) as String
Declare CurrentFileName2 array (0 to 5) as String
Declare outputFile array (8) as String

```

While Device.Name in Database Device Table <> End of File
  If (Device 33kV Min Cost file <> "") Then
    Open Device 33kV Cable Cost as CurrentFileName1(0)

```


Open Device 132kV Cable Cost as CurrentFileName1(1)
Open Device HVDC Cable Cost file as CurrentFileName1(2)

Open Device 33kV Min Cost file as CurrentFileName2(0)
Open Device 33kV Max Cost file as CurrentFileName2(1)
Open Device 132kV Min Cost file as CurrentFileName2(2)
Open Device 132kV Max Cost file as CurrentFileName2(3)
Open Device HVDC Min Cost file as CurrentFileName2(4)
Open Device HVDC Max Cost file as CurrentFileName2(5)

Open Device/Cable 33kV Min Cost file for Random Access as outputFile(0)
Open Device/Cable 33kV Max Cost file for Random Access as outputFile(1)
Open Device/Cable 132kV Min Cost file for Random Access as outputFile(2)
Open Device/Cable 132kV Max Cost file for Random Access as outputFile(3)
Open Device/Cable HVDC Min Cost file for Random Access as outputFile(4)
Open Device/Cable HVDC Max Cost file for Random Access as outputFile(5)

Set Count to 0

For each x (x = 0 to 2)

For each record row (j) (j = 1 to 450)

Read into dataStructure1(x) the (j) record of the file set at
CurrentFileName(x)

Read into dataStructure2 (count) the (j) record of the file set at
CurrentFileName2(count)

Read into dataStructure2 (count + 1) the (j) record of the file set at
CurrentFileName2(count + 1)

For each column (i) (i = 0 to 519)

costArray(count).column(i) = ""

costArray(count + 1).column(i) = ""

If (dataStructure2(count).column(i) = "NA") Then

costArray(count).column(i) = "NA"

costArray(count + 1).column(i) = "NA"

Else if (dataStructure2(count).column(i) = "na") Then

costArray(count).column(i) = "na"

costArray(count + 1).column(i) = "na"

Else

costArray(count).column(i) = dataStructure1(x).column(i) +
dataStructure2(count).column(i)

costArray(count + 1).column(i) = dataStructure1(x).column(i) +
dataStructure2(count + 1).column(i)

End if

Increment i

Write CostArray(count) to (j) record of outputFile (count)

Write CostArray(count + 1) to (j) record of outputFile (count + 1)

Increment j

Increment count by 2

Increment x

Close Device 33kV Cable Cost file
Close Device 132kV Cable Cost file
Close Device HVDC Cable Cost file

Close Device 33kV Min Cost file
 Close Device 33kV Max Cost file
 Close Device 132kV Min Cost file
 Close Device 132kV Max Cost file
 Close Device HVDC Min Cost file
 Close Device HVDC Max Cost file

 Close Device/Cable 33kV Min Cost file
 Close Device/Cable 33kV Max Cost file
 Close Device/Cable 132kV Min Cost file
 Close Device/Cable 132kV Max Cost file
 Close Device/Cable HVDC Min Cost file
 Close Device/Cable HVDC Max Cost file
 End if
 Move to next Device

J.11 Calculate revenue at each site for each valid device

Declare dataStructure array (0 to 5) as column (520) with 3 digits per field
 Declare valueArray array (0 to 5) as column (520) with 9 digits per field
 Declare CurrentFileName array (0 to 5) as String
 Declare OutputFile array (0 to 5) as String

While ModelData <> End of File
 If (ModelData.Name = "Unit price of electricity") Then
 UnitPriceOfElec = ModelData.value
 End if
 Move to next ModelData

While Device.Name in Database Device Table <> End of File
 If (Device 33kV Min Number file <> "") Then
 Open Device 33kV Min Number file as CurrentFileName(0)
 Open Device 33kV Max Number file as CurrentFileName(1)
 Open Device 132kV Min Number file as CurrentFileName(2)
 Open Device 132kV Max Number file as CurrentFileName(3)
 Open Device HVDC Min Number file as CurrentFileName(4)
 Open Device HVDC Max Number file as CurrentFileName(5)

 Open Device Revenue 33kV Min Income file for Random Access as outputFile(0)
 Open Device Revenue 33kV Max Income file for Random Access as outputFile(1)
 Open Device Revenue 132kV Min Income file for Random Access as outputFile(2)
 Open Device Revenue 132kV Max Income file for Random Access as outputFile(3)
 Open Device Revenue HVDC Min Income file for Random Access as outputFile(4)
 Open Device Revenue HVDC Max Income file for Random Access as outputFile(5)

For each x (x = 0 to 5)
 For each record row (j) (j = 1 to 450)
 Read into dataStructure(x) the (j) record of the file set at CurrentFileName(x)
 For each column (i) (i = 0 to 519)
 valueArray(count).column(i) = ""
 If (dataStructure(x).column(i) = "NA") Then

```

        valueArray(x).column(i) = "NA"
    Else if (dataStructure(x).column(i) = "na") Then
        valueArray(x).column(i) = "na"
    Else
        valueArray(x).column(i) = dataStructure(x).column(i) *
        UnitPriceOfElec
    End if
    Increment i
    Write valueArray(x) to (j) record of outputFile (x)
    Increment j
Increment x

Close Device 33kV Min Number file
Close Device 33kV Max Number file
Close Device 132kV Min Number file
Close Device 132kV Max Number file
Close Device HVDC Min Number file
Close Device HVDC Max Number file
Close Device Revenue 33kV Min Income file
Close Device Revenue 33kV Max Income file
Close Device Revenue 132kV Min Income file
Close Device Revenue 132kV Max Income file
Close Device Revenue HVDC Min Income file
Close Device Revenue HVDC Max Income file
End if
Move to next Device

```

J.12 Calculate installation depth factor for each site

```

Declare dataStructure1 as column (520) with 2 digits per field
Declare dataStructure2 as column (520) with 4 digits per field
Declare outputStructure as column (520) with 3 digits per field
Declare valueArray as column (520) with 3 digits per field

While Device.Name in Database Device Table <> End of File
    If (Device by Union file <> "") Then
        Open Device by Union file
        Open DTI Water Depth file
        Open Installation Depth Factor file for Random Access
        For each record row (j) (j = 1 to 450)
            Read into dataStructure1 the (j) record of the Device by Union file
            Read into dataStructure2 the (j) record of the DTI Water Depth file
            For each column (i) (i = 0 to 519)
                valueArray.column(i) = ""
                If (dataStructure1.column(i) = "NA") Then
                    valueArray.column(i) = "NA"
                Else if (dataStructure1.column(i) = "na") Then
                    valueArray.column(i) = "na"
                Else
                    While DepthFactor table in Database <> End of File
                        If (dataStructure2.column(i) <= DepthFactor.Depth&

```

```

        dataStructure2.column(i) >= DepthFactor.Depth2) Then
            valueArray.column(i) = DepthFactor.Factor
        End if
        Move to next DepthFactor
    End if
    Increment i
    Write valueArray to (j) record of Installation Depth Factor file
    Increment j
End if

Close Device by Union file
Close DTI Water Depth file
Close Installation Depth Factor file
Move to next Device

```

J.13 Calculate installation distance factor for each site

For the logic of this method please refer to: *J.12 Calculate installation depth factor for each site* above. The only differences in the two methods is the output file name (Installation Distance Factor file), the database table name which is DistanceFactor rather than DepthFactor and the variable names that associated with the Database tables, i.e. Depth Factor.Depth would read DistanceFactor.Distance. To calculate the factor the Port Distance file is used rather than the DTI Water Depth file.

J.14 Calculate overall installation costs

```

Declare dataStructure1 array (0 to 5) as column (520) with 3 digits per field
Declare dataStructure2 array (0 to 5) as column (520) with 5 digits per field
Declare valueArray array (0 to 5) as column (520) with 9 digits per field
Declare CurrentFileName array (0 to 7) as String
Declare OutputFile array (0 to 5) as String

```

While Device.Name in Database Device Table <> End of File

 If (Device Installation Depth Factor File <> "") Then

```

    Open Device 33kV Min Number file as CurrentFileName(0)
    Open Device 33kV Max Number file as CurrentFileName(1)
    Open Device 132kV Min Number file as CurrentFileName(2)
    Open Device 132kV Max Number file as CurrentFileName(3)
    Open Device HVDC Min Number file as CurrentFileName(4)
    Open Device HVDC Max Number file as CurrentFileName(5)

```

```

    Open Device Installation Depth Factor file as CurrentFileName(6)
    Open Device Installation Distance Factor file as CurrentFileName(7)

```

```

    Open Device 33kV Min Installation Cost file for Random Access as outputFile(0)
    Open Device 33kV Max Installation Cost file for Random Access as outputFile(1)

```

Open Device 132kV Min Installation Cost file for Random Access as outputFile(2)
 Open Device 132kV Max Installation Cost file for Random Access as outputFile(3)
 Open Device HVDC Min Installation Cost file for Random Access as outputFile(4)
 Open Device HVDC Max Installation Cost file for Random Access as outputFile(5)

While MooringFactor () End of File
 If (MooringFactor.Method = Devices.Mooring Type Then
 numberOfDays = MooringFactor.Factor
 End if
 Move to next ModelData

For each x (x = 0 to 5)
 For each record row (j) (j = 1 to 450)
 Read into dataStructure1(0) the (j) record of the file set at CurrentFileName(6)
 Read into dataStructure1(1) the (j) record of the file set at CurrentFileName(7)
 Read into dataStructure2 the (j) record of the file set at CurrentFileName(x)
 For each column (i) (i = 0 to 519)
 valueArray(x).column(i) = ""
 If (dataStructure2(x).column(i) = "NA") Then
 valueArray(x).column(i) = "NA"
 Else if (dataStructure2(x).column(i) = "na") Then
 valueArray(x).column(i) = "na"
 Else
 If (Devices.Daily Installation Cost \neq "") Then
 valueArray(x).column(i) = dataStructure2(x).column(i) *
 Devices.Daily Installation Cost * numberOfDays *
 dataStructure1(0).column(i) * dataStructure1(1).column(i)
 Else
 valueArray(x).column(i) = "na"
 End if
 End if
 Increment i
 Write valueArray(x) to (j) record of outputFile (x)
 Increment j
 Increment x

Close Device 33kV Min Number file
 Close Device 33kV Max Number file
 Close Device 132kV Min Number file
 Close Device 132kV Max Number file
 Close Device HVDC Min Number file
 Close Device HVDC Max Number file
 Close Device Installation Depth Factor file
 Close Device Installation Distance Factor file
 Close Device 33kV Min Installation Cost file
 Close Device 33kV Max Installation Cost file
 Close Device 132kV Min Installation Cost file
 Close Device 132kV Max Installation Cost file
 Close Device HVDC Min Installation Cost file
 Close Device HVDC Max Installation Cost file

End if
 Move to next Device

J.15 Add installation costs to device and cable costs

Declare dataStructure1 array (0 to 5) as column (520) with 9 digits per field
Declare dataStructure2 array (0 to 5) as column (520) with 9 digits per field
Declare valueArray array (0 to 5) as column (520) with 9 digits per field
Declare CurrentFileName1 array (0 to 5) as String
Declare CurrentFileName2 array (0 to 5) as String
Declare OutputFile array (0 to 5) as String

While Device.Name in Database Device Table <> End of File

 If (Device 33kV Min Installation Cost file <> "") Then

 Open Device 33kV Min Installation Cost file as CurrentFileName1(0)
 Open Device 33kV Max Installation Cost file as CurrentFileName1(1)
 Open Device 132kV Min Installation Cost file as CurrentFileName1(2)
 Open Device 132kV Max Installation Cost file as CurrentFileName1(3)
 Open Device HVDC Min Installation Cost file as CurrentFileName1(4)
 Open Device HVDC Max Installation Cost file as CurrentFileName1(5)

 Open Device 33kV Min Device\Cable Cost file as CurrentFileName2(0)
 Open Device 33kV Max Device\Cable Cost file as CurrentFileName2(1)
 Open Device 132kV Min Device\Cable Cost file as CurrentFileName2(2)
 Open Device 132kV Max Device\Cable Cost file as CurrentFileName2(3)
 Open Device HVDC Min Device\Cable Cost file as CurrentFileName2(4)
 Open Device HVDC Max Device\Cable Cost file as CurrentFileName2(5)

 Open Device 33kV Min Overall Costs file for Random Access as outputFile(0)
 Open Device 33kV Max Overall Costs file for Random Access as outputFile(1)
 Open Device 132kV Min Overall Costs file for Random Access as outputFile(2)
 Open Device 132kV Max Overall Costs file for Random Access as outputFile(3)
 Open Device HVDC Min Overall Costs file for Random Access as outputFile(4)
 Open Device HVDC Max Overall Costs file for Random Access as outputFile(5)

 For each x (x = 0 to 5)

 For each record row (j) (j = 1 to 450)

 Read into dataStructure1 the (j) record of the file set at CurrentFileName1(x)

 Read into dataStructure2 the (j) record of the file set at CurrentFileName2(x)

 For each column (i) (i = 0 to 519)

 valueArray(x).column(i) = ""

 If (dataStructure2(x).column(i) = "NA") Then

 valueArray(x).column(i) = "NA"

 Else if (dataStructure2(x).column(i) = "na") Then

 valueArray(x).column(i) = "na"

 Else

 valueArray(x).column(i) = dataStructure1(x).column(j) +

 dataStructure2(x).column(j)

 End if

 Increment i

 Write valueArray(x) to (j) record of outputFile (x)

 Increment j

 Increment x

Close Device 33kV Min Installation Cost file
 Close Device 33kV Max Installation Cost file
 Close Device 132kV Min Installation Cost file
 Close Device 132kV Max Installation Cost file
 Close Device HVDC Min Installation Cost file
 Close Device HVDC Max Installation Cost file
 Close Device 33kV Min Device\Cable Cost file
 Close Device 33kV MaxDevice\Cable Cost file
 Close Device 132kV Min Device\Cable Cost file
 Close Device 132kV Max Device\Cable Cost file
 Close Device HVDC Min Device\Cable Cost file
 Close Device HVDC Max Device\Cable Cost file
 Close Device 33kV Min Overall Costs file
 Close Device 33kV Max Overall Costs file
 Close Device 132kV Min Overall Costs file
 Close Device 132kV Max Overall Costs file
 Close Device HVDC Min Overall Costs file
 Close Device HVDC Max Overall Costs file
 End if
 Move to next Device

J.16 Determine profit/loss for each valid device at each valid site

Declare dataStructure array (0 to 11) as column (520) with 9 digits per field
 Declare valueArray array (0 to 5) as column (520) with 9 digits per field
 Declare CurrentFileName1 array (0 to 5) as String
 Declare CurrentFileName2 array (0 to 5) as String
 Declare OutputFile array (0 to 5) as String

While Device.Name in Database Device Table <> End of File

If (Device 33kV Min Overall Costs file <> "") Then

Open Device 33kV Min Overall Costs file as CurrentFileName1(0)
 Open Device 33kV Max Overall Costs file as CurrentFileName1(1)
 Open Device 132kV Min Overall Costs file as CurrentFileName1(2)
 Open Device 132kV Max Overall Costs file as CurrentFileName1(3)
 Open Device HVDC Min Overall Costs file as CurrentFileName1(4)
 Open Device HVDC Max Overall Costs file as CurrentFileName1(5)

Open Device Revenue 33kV Min Income file as CurrentFileName2(0)
 Open Device Revenue 33kV MaxIncome file as CurrentFileName2(1)
 Open Device Revenue 132kV Min Income file as CurrentFileName2(2)
 Open Device Revenue 132kV Max Income file as CurrentFileName2(3)
 Open Device Revenue HVDC Min Income file as CurrentFileName2(4)
 Open Device Revenue HVDC Max Income file as CurrentFileName2(5)

Open Device 33kV Min Profit Loss file for Random Access as outputFile(0)
 Open Device 33kV Max Profit Loss file for Random Access as outputFile(1)
 Open Device 132kV Min Profit Loss file for Random Access as outputFile(2)
 Open Device 132kV Max Profit Loss file for Random Access as outputFile(3)
 Open Device HVDC Min Profit Loss file for Random Access as outputFile(4)
 Open Device HVDC Max Profit Loss file for Random Access as outputFile(5)

```

For each x (x = 0 to 5)
  For each record row (j) (j = 1 to 450)
    Read into dataStructure(x) the (j) record of the file set at CurrentFileName1(x)
    Read into dataStructure (x +6) the (j) record of the file set at
    CurrentFileName2(x +6)
    For each column (i) (i = 0 to 519)
      valueArray(x).column(i) = ""
      If (dataStructure(x).column(i) = "NA") Then
        valueArray(x).column(i) = "NA"
      Else if (dataStructure(x).column(i) = "na") Then
        valueArray(x).column(i) = "na"
      Else
        valueArray(x).column(i) = dataStructure(x +6).column(j) -
        dataStructure(x).column(j)
      End if
      Increment i
    Write valueArray(x) to (j) record of outputFile (x)
  Increment j
Increment x

Close Device 33kV Min Overall Costs file as CurrentFileName1(0)
Close Device 33kV Max Overall Costs file
Close Device 132kV Min Overall Costs file
Close Device 132kV Max Overall Costs file
Close Device HVDC Min Overall Costs file
Close Device HVDC Max Overall Costs file
Close Device Revenue 33kV Min Income file
Close Device Revenue 33kV Max Income file
Close Device Revenue 132kV Min Income file
Close Device Revenue 132kV Max Income file
Close Device Revenue HVDC Min Income file
Close Device Revenue HVDC Max Income file
Close Device 33kV Min Profit Loss file for Random Access
Close Device 33kV Max Profit Loss file for Random Access
Close Device 132kV Min Profit Loss file for Random Access
Close Device 132kV Max Profit Loss file for Random Access
Close Device HVDC Min Profit Loss file for Random Access
Close Device HVDC Max Profit Loss file for Random Access
End if
Move to next Device

```

J.17 Calculate Distance

```

Accept from calling methods: Latitude Distance, Longitude Distance, Holding Degree
Value, Latitude Seconds, overallDistance.
Declare DegreesLAT as Double
Declare RadiusLAT as Double
Declare CircumferenceLAT as Double
Declare DistancePerDegreeLONG as Double
Declare DistancePerDegreeNM as Double
Declare longCorrection as Double

```



```

Declare latDistanceNaut as Double
Declare longDistanceNaut as Double
Declare pi as Double (4 * Atn(1))
Declare EquatorialRadius as Double (6378.135)

latDistanceNaut = (latDistance / 60)
longDistanceNaut = (longDistance / 60)
DegreesLAT = ((latSeconds + holdingDegreeValue) / 2) / 3600
DegreesLAT = DegreesLAT * (pi / 180)
RadiusLAT = EquatorialRadius * Cosine(DegreesLAT)
CircumferenceLAT = RadiusLAT * 2 * pi
DistancePerDegreeLONG = CircumferenceLAT / 360
DistancePerDegreeNM = DistancePerDegreeLONG / 1.852
longCorrection = (longDistance / 3600) * DistancePerDegreeNM
overallDistance = Square root((latDistanceNaut * latDistanceNaut) + (longCorrection *
longCorrection))

Return overallDistance to calling method.

```

APPENDIX K, GUIDE TO ACCOMPANYING ELECTRONIC MATERIAL

K.1 Software used and compatibility

Overall software application – constructed in Visual Basic 6.0 enterprise edition on the Windows XP operating system with forward tested compatibility with Windows 7.

Database files – stored in Microsoft Access tables. Microsoft Access version 2000 with forward tested compatibility to version 2010. This includes both the input database (mother database) and results database.

Input files – formatted using various methods of Visual Basic and Visual Basic for Applications (VBA). Stored in .txt format and can be opened in any text editor such as Microsoft Notepad. Care must be taken as these are stored in the random access format and all spaces are important to the structure of the file.

Output files – formatted and produced using Visual Basic. Stored in .txt format and can be opened in any text editor such as Microsoft Notepad. Care must be taken as these are stored in the random access format and all spaces are important to the structure of the file.

K.2 Submitted electronic program files

All files and scripts used to: construct, format, and program are included within the attached DVD data. These are in differing formats such as Microsoft Excel, Microsoft Visual Basic, and Visual Basic for Applications. Therefore to view (and certainly to execute) these files correctly the reader may need the relevant software. The versions used and compatibility is described at *K.1*.

K.3 Program data

All model data described within this thesis is available in the attached DVD data. This includes the 9 data test and illustration runs undertaken as part of the model description in *Chapter 5* and *Chapter 6*.

K.4 Installing and using software application

The attached DVD data contains a Readme.txt file within the root directory which contains the same information as this section, which is designed to instruct the user in installing and using the software application.

When opening DVD disc 1 (which will likely be mapped to drive d:\) there is a *Setup.bat* file which when run will copy the contents of the DVD to the local machine currently in use. This will save the files to “C:\Mark Wemyss PhD Hand in”. It is highly recommended the model is run from the local hard drive. Once the batch file is ready for the second DVD disc to be installed the user is prompted.

The files within the DVD’s could be copied manually to another desired location. However, if the program is not run from the default location (“C:\Mark Wemyss PhD Hand in”) then the working directory within the database (pointer to where input data files are read and output files to be written) has to be changed. For example if the program is copied to the user’s desktop then the following has to be undertaken. Firstly load the database (“Access 2000 Mother Database”) within the “C:\Mark Wemyss PhD Hand in\Computer modelling\Visual Basic Version\Data” directory. Once loaded, open the “Model Values” table and change the path (“Value”) of the working directory entry, to the new location of the model data. In the instance of the desktop example above, the path would need to be changed to “c:\documents and settings\%username%\desktop” where %username% is the account the user is currently logged in as. Incidentally, the path to the desktop within Windows XP and Windows 7 is different, however Windows 7 will recognise the older XP path and convert to the correct location. Every input database used by the model will need to be changed in the same way.

The setup file will also create a short cut to the hand in directory (“C:\Mark Wemyss PhD Hand in”) and a short cut to the application model executable (.exe) file which are both placed on the user desktop. These are named: “Mark Wemyss PhD Hand In” which will open the main project directory of the same name on the root of C drive, and “Application Model” which will automatically run the application model.

This should prevent any need to copy the entire project hand in file to the desktop or any other location. It is advisable to leave the project installed in the default location. It

is also advisable not to transfer the entire project files to the desktop, as large amounts of data on the desktop can cause Windows profiling/account problems, as well as the need to alter the pointer paths as already described.

The file structure of the C:\Mark Wemyss PhD Hand is displayed in *Figure K.1* which is a Window 7 display format.

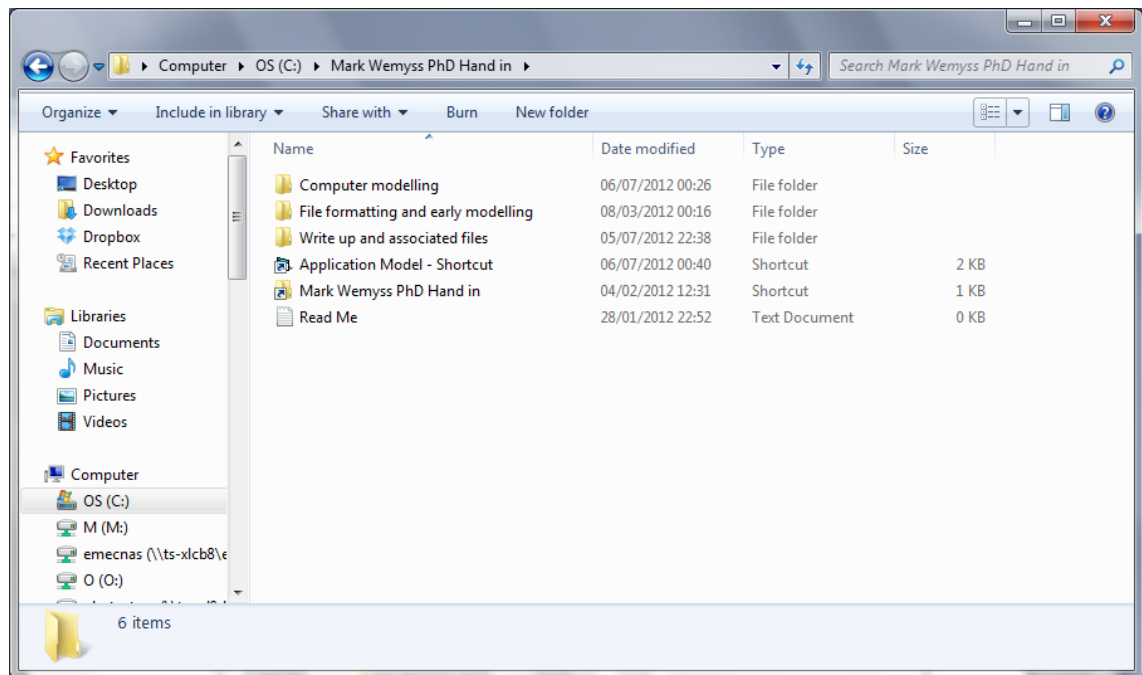


Figure K.1 showing the structure of the C:\Mark Wemyss PhD Hand in.

The “Computer modelling” folder contains all the input/output data, program modules and anything else related to the software build. The “File formatting and early modelling” contains a collection of the scripts and MS Excel applications constructed for file and data manipulation, which is described within *Chapter 2*. The “Write up and associated files” contains a copy of this thesis and other documentation associated with the write up. The “Application Model” file is a shortcut to the executable (.exe) file that will launch the model application. Rather than explain the workings and usability of the model in this section, the reader can refer to *Chapter 4* of the thesis where a step by step walkthrough is given.

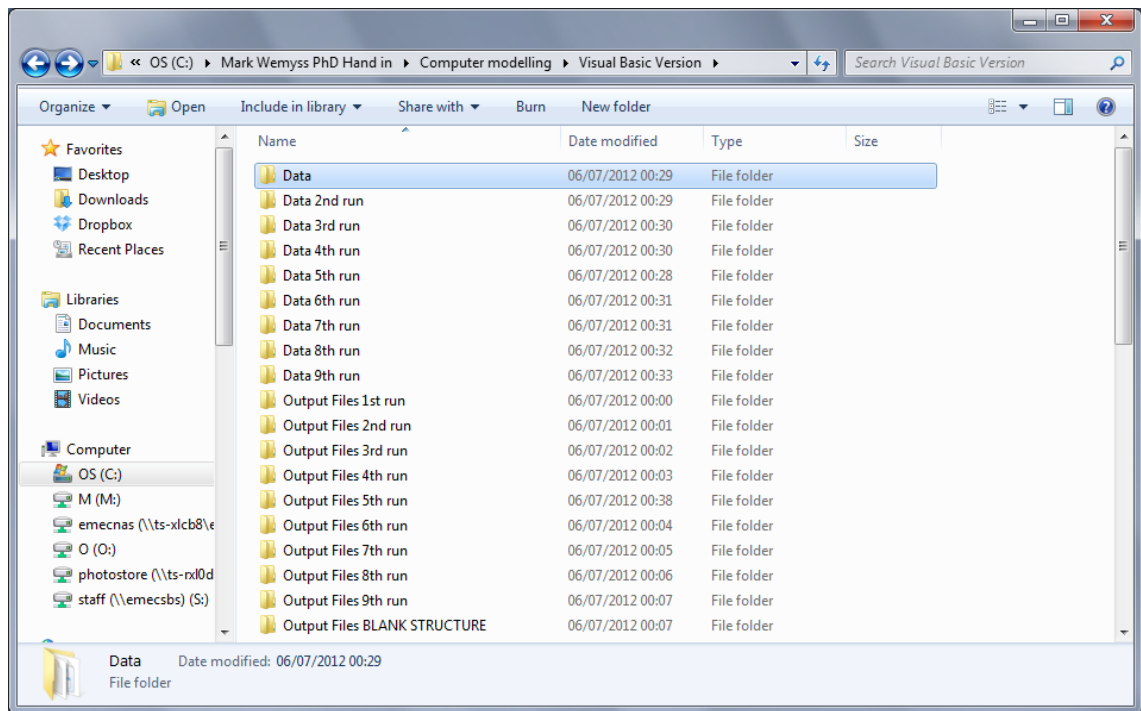


Figure K.2 showing the structure of the “C:\Mark Wemyss PhD Hand in\Computer modelling\Visual Basic Version”.

The folder “Visual Basic Version” within the “Computing modelling” folder contains the entire Visual Basic work undertaken to construct the application, which includes all the code and forms. This allows the user to view, edit, recompile any of the work undertaken. This folder also contains the data input and output results which were used/created by the model during the testing and illustrations carried out in *Chapters 5 and 6*. The output files can be viewed, and to recreate any of the test runs undertaken in *Chapters 5 and 6*, rename the desired data directory (which will be named: “Data”, “Data 2nd run”, “Data 3rd run”, “Data 4th run”, “Data 5th run” and so on) to simply “Data” as the model looks for the input data saved in a directory with this specific name. The “Data” folder in this directory is the data for the first model run which is the data that will be loaded when the model is run. If any of the other run data is to be loaded rename the “Data” folder to “Data 1st run” and the desired run folder to “Data”. Care must be taken to rename the folders back to the correct run index when various data folders are used in succession.

The Output Files folders were used by the application for the various output result files. When the model is run an “Output Files” folder is created automatically so care must be taken to save (rename) any previous runs if the user does not wish to lose these.

Shown within *figure K.2* is the various output files from the previous runs that have been renamed and therefore saved.